The Benefits of Daylight through Windows

Peter Boyce, Claudia Hunter and Owen Howlett

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Executive Summary

The use of daylight as the primary light source in buildings is of interest to those concerned with energy conservation because it is assumed to minimize the use of electricity for lighting. However, it is difficult to justify the cost of extensive daylighting on the basis of energy savings alone. Rather, to justify the widespread use of daylight in buildings it is necessary to demonstrate that such use has a beneficial financial impact for the organization owning and/or occupying the building. This literature review considers the impact of daylight on human performance and workplace productivity; human health; and financial return on investment. These impacts of daylight are reviewed for buildings that are used for work and for which daylighting has been extensively studied, namely offices, schools, hospitals, and retail stores. Daylight in housing is not considered. This literature review examines the benefits and problems of both daylight, as light, and windows, as the most commonly used method to deliver daylight. From this literature review, a research agenda is developed.

The following conclusions are drawn from the literature review:

1. Physically, daylight is just another source of electromagnetic radiation in the visible range. Electric light sources can be constructed to closely match a spectrum of daylight, but none have been made that mimic the variation in light spectrum that occurs with daylight at different times, in different seasons, and under different weather conditions.

2. Physiologically, daylight is an effective stimulant to the human visual system and the human circadian system.

3. Psychologically, daylight and a view are much desired.

4. The performance of tasks limited by visibility is determined by the stimuli the task presents to the visual system and the operating state of that system. Daylight is not inherently better than electric light in determining either of these factors. However, daylight does have a greater probability of maximizing visual performance than most forms of electric lighting because it tends to be delivered in large amounts with a spectrum that ensures excellent color rendering.

5. There can be no guarantee that daylight will always be successful in maximizing visual performance. Daylight can cause visual discomfort through glare and distraction, and it can diminish the stimuli the task presents to the visual system by producing veiling reflections or by shadows. The effectiveness of daylight for visual performance will depend on how it is delivered. The same conclusion applies to electric lighting

6. People will take action to reduce or eliminate daylight if it causes discomfort or increases task difficulty.

7. The performance of both visual and non-visual tasks will be affected by disruption of the human circadian system. A disrupted circadian system will also create long-term health problems. Exposure to bright light during the day and little or no light at night will accurately entrain the circadian system. Daylighting is an attractive way to deliver bright light during the day.

8. Different lighting conditions can change the mood of occupants of a building. However, there is no simple recipe for what lighting conditions produce the most positive mood. Windows are strongly favored in work places for the daylight they deliver and the view out they provide, as long as they do not cause visual or thermal discomfort or a loss of privacy. Whether windows will produce an improvement in mood seems to depend on what the individual's preferences and expectations are. For people who prefer daylight but who have become accustomed to little daylight, moving into a well daylighted space can be expected to lead to an improvement in mood that will diminish over time as new expectations are established. For people who prefer daylight and who are accustomed to a lot of daylight, moving into a space with little daylight is likely to lead to a deterioration in mood that will recover over time.

9. The understanding of how mood influences productivity is weak. Different studies have emphasized worker happiness, well-being, and job satisfaction as predictors of productivity while others have suggested that productivity is itself a generator of feelings of happiness, well-being, and job satisfaction. The basic problem for daylighting is that mood is subject to so many influences that unless the lighting is really uncomfortable, its influence is likely to be overshadowed by many other factors.

10. Exposure to daylight can have both positive and negative effects on health.

The strongest effects occur outdoors. Exposure to daylight outdoors can cause tissue damage, which is bad, and generate vitamin D, which is good. Daylight and sunlight delivered through glass will have much less short wavelength ultra-violet (UV-B) radiation than the same radiation outdoors, but can still have adverse effects on people who are sensitive to ultra-violet radiation. Daylighting that makes what needs to be seen difficult to see can cause eyestrain. Conversely, daylighting that makes what needs to be seen easy to see can reduce eyestrain. Windows that provide a view out as well as daylight, can reduce stress and hence reduce the demand for health services. Daylight reduces the incidence of health problems caused by the rapid fluctuations in light output typical of electric lighting.

11. A wall containing windows costs more to construct and maintain than one without. These costs may be offset by reductions in building operating costs. However, the presence of windows is believed to have a positive effect on the rental value of a space.

12. Daylighting of a conventionally windowless retail space can have a positive effect on sales.

From these conclusions, four topics that deserve research stand out. They are:

- Reducing the likelihood of discomfort from windows, so as to minimize behaviors that limit the admission of daylight

- Quantifying the financial return on windows in terms of what people are prepared to pay for them, regardless of the reasons why

- Exploring the impact of daylight operating through the human circadian system on task performance

- Testing the biophilia hypothesis; i.e., that humans have an innate need to be in contact with nature. This is important because it is the main reason why windows are inherently superior to electric lighting

There are many other topics that could be examined, but some, such as examining the effect of daylight on visual performance, seem unnecessary as knowledge in that area is already sufficient to predict the results. Others, such as examining the effect of daylighting on mood and hence productivity, could be undertaken but given the amount of work that has already been done in this area and the confusing pattern of results obtained, the probability of success is low.

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1. Background

The use of daylight as the primary source of lighting in buildings has been advocated for many years, with mixed results. Over the decades since the widespread introduction of electric lighting, the pendulum of architectural fashion has swung to and fro, sometimes emphasizing the ability to provide a stable and comfortable indoor environment regardless of the external conditions, the engineering approach; and sometimes emphasizing the desirability of natural things, the biological approach. Currently, the emphasis is on sustainable buildings that have a minimal impact on the environment (Selkowitz, 1998, Heerwagen and Wise, 1998). The use of daylight as the primary light source is an integral part of sustainable buildings because it is assumed to minimize the use of electricity. However, the widespread occurrence of multi-occupied spaces which inhibit the use of manual controls, the limitations of automatic lighting control systems in practice, and the reduced power density of modern electric lighting systems, have made it difficult to justify the cost of extensive daylighting on the basis of potential energy savings alone. Rather, to justify the widespread use of daylight in buildings it is necessary to demonstrate that such use has beneficial effects in other areas, areas that have a financial impact for the organization owning and/or occupying the building. This literature review seeks to identify what such areas might be; what is known about the impact of daylight in those areas, and what is not known. This literature review examines the benefits and problems of both daylight, as light, and windows, as the most commonly used method to deliver daylight. From this literature review, a research agenda is developed.

2. Significant impacts of daylighting

From the point of view of an organization occupying a building, some form of lighting is a necessity but it is not an end in itself. Rather lighting is a means to an end. The end in question is the ability for the organization to flourish, which means it must be able to fulfil the purpose for which it exists. For this to happen, the people who work in the building should be healthy and productive, and the lighting must support the activities the people are there to undertake.

From the point of view of an organization constructing a building for its own use or for lease, there are many financial aspects that need to be considered. These can be on the cost side; i.e., what does it cost to provide daylight in a building, or on the benefit side; i.e., does having daylight in a building have an impact on the costs of operating the building or on the rent that might be achieved.

It is these impacts of daylight: human performance and workplace productivity; human health; and financial return on investment, that will be considered in this review. The impacts of daylight will be reviewed in the context of buildings used for work and for which daylighting has been extensively studied, namely offices, schools, hospitals, and retail stores. Daylight in housing will not be considered.

3. Enhancing productivity

The productivity of an individual or an organization can be defined as the ability to enhance work output through increases in either quantity and/or quality of the product or service to be delivered. Productivity at work can be measured in many different ways and is influenced by many different factors (Clements-Croome and Kaluarachi, 2000). Figure 1 shows a schematic of the factors that are known to influence productivity at work, derived from the analytic hierarchy process developed by Saaty (1972). Figure 1 shows that productivity is influenced by both the individual and the system within which he / she works. The indoor environment, including lighting conditions, is one of the system factors that influence the productivity of the individual.

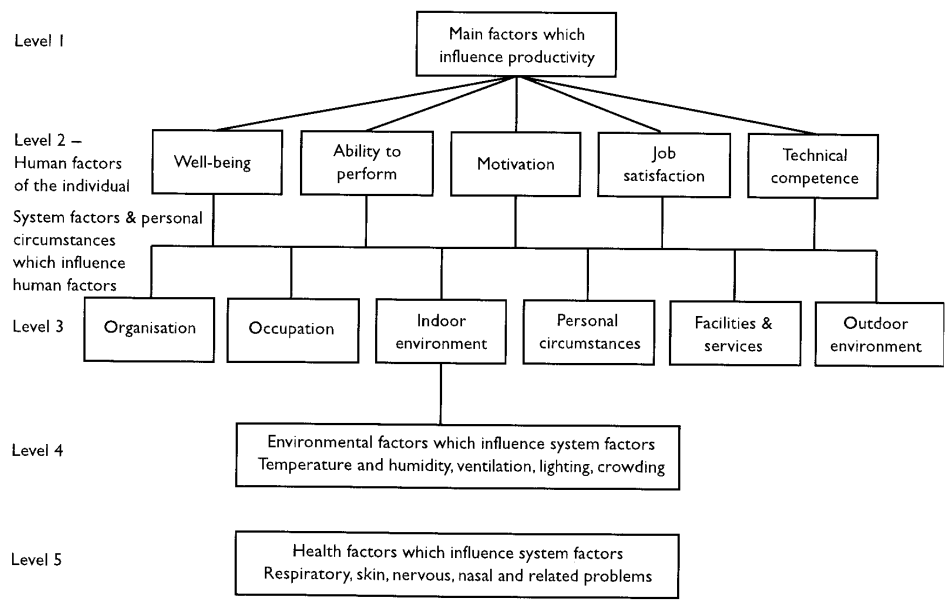

Figure 1: A schematic of factors known to influence productivity at work

3.1 How lighting conditions can impact individual human performance

Synopsis: There are three routes by which lighting conditions can influence the performance of individuals: through the visual system, through the circadian system and through the perceptual system. The capabilities of the visual system are determined by the lighting conditions. The state of the circadian system is influenced primarily by the light - dark cycle. The "message" delivered by the perceptual system is influenced by many factors, lighting being just one of them.

Figure 2 shows a conceptual framework for considering how lighting conditions influence human performance through the visual system, through the circadian system, and through the perceptual system progress

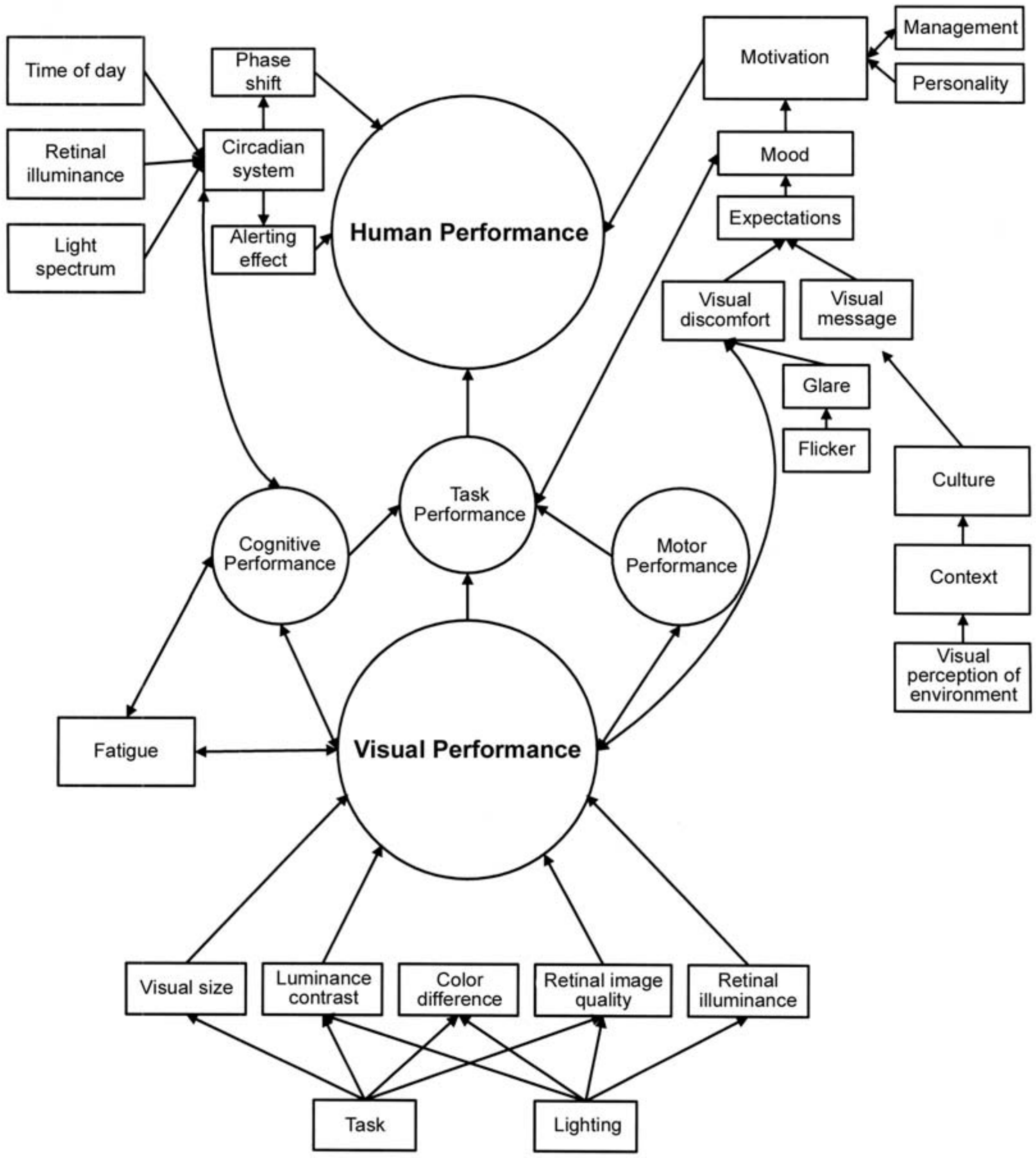

Figure 2: A conceptual framework setting out the routes by which lighting can influence human performance. The arrows indicate the direction of the effects (Boyce and Rea, 2001).

The effect of lighting on vision is the most obvious impact of light on humans. With light we can see, without light we cannot. Any stimulus to the visual system can be described by five basic parameters: visual size, luminance contrast, color difference, retinal image quality and retinal illumination. These parameters are important in determining the extent to which the visual system can detect and identify the stimulus. The direction of the effect is such that the larger the visual size, the higher the luminance contrast, the greater the color differences, the better the retinal image quality, and the higher the retinal illumination, the faster and finer will be the performance of the visual system. It is the interaction between the characteristics of the task and the amount, spectrum, and distribution of the lighting of the task that determines what level of performance is achieved.

Lighting conditions can also affect human performance through the circadian system. The most obvious evidence for the existence of a circadian system in humans is the occurrence of the sleep / wake cycle, but this is only the tip of the iceberg. Beneath the surface lie the variations in many different hormonal rhythms over a twenty-four hour period. Lighting conditions over twenty-four hours, specifically the light - dark cycle, are major factors in determining the state of the circadian system, and that itself will influence the performance of all tasks, not just visual tasks. Our knowledge of how lighting conditions might affect human performance through the circadian system has grown rapidly in recent years. There are two distinct effects; a shifting effect in which the phase of the circadian rhythm can be advanced or delayed by exposure to bright light at specific times (Dijk et al., 1995); and an acute effect related to the suppression of the hormone melatonin at night (Campbell et al., 1995). Both these effects can be expected to enhance human performance in the right circumstances. Attempts have been made to use the phase-shift to more quickly adapt people to night shift work. These attempts have met with mixed success, the problem being that to get the required shift, it is necessary to control exposure to light over 24 hours, not just during working hours (Eastman et al., 1994). As for the acute effect, there is clear evidence that exposure to bright light increases alertness at night (Badia et al., 1991) and that this can enhance the performance of complex cognitive tasks (Boyce et al., 1997).

The third route whereby lighting conditions can affect human performance is through the perceptual system. The perceptual system takes over once the retinal image has been processed by the visual system. The output of the perceptual system that is most likely to change the observer's mood and behavior, particularly if work is prolonged, is a sense of discomfort. Lighting conditions in which achieving a high level of visual performance is difficult will be considered uncomfortable as will conditions in which the lighting leads to distraction from the task, as can occur when glare and flicker are present. But perception is much more sophisticated than just producing a feeling of visual discomfort. In a sense, every lighting installation sends a "message" about the people who designed it, who bought it, who work under it, who maintain it, and about the place it is located. Observers interpret the "message" according to the context in which it occurs and their own culture, preferences and expectations. The importance of this "message" is sometimes enough to override conditions that might be expected to cause discomfort, as shown by the fact that lighting conditions that would be considered extremely uncomfortable in an office are positively desired in a dance club. According to what the "message" is, the observer's mood and behavior can be changed.

While each of these routes has been discussed separately, it is important to appreciate that they can also interact. For example, someone who is asked to work while sleep-deprived will be fatigued. This fatigue will affect task performance through both its cognitive and visual components. Conversely, people who are performing a task that is visually difficult for a long time will experience fatigue, even if they are not sleep-deprived. Another example would be a situation where the lighting provides poor task visibility, so that visual performance is poor. If the worker is aware of the poor level of performance and it fails to meet his or her expectations, then frustration may develop and the worker's mood may be altered. Multiple interactions of this type can occur. To further complicate the picture, it is necessary to appreciate that while visual performance for a given task is determined by the lighting conditions alone, a worker's mood and motivation can be influenced by many other factors. As for the circadian system, this can be influenced by such factors as the timing of exercise and social cues as well as light exposure (Van Reeth et al., 1994). It is this complex pattern of interacting effects that has made the study of the relationship between lighting and human performance so prolonged and difficult.

3.2 The shape of visual performance

Synopsis: Visual performance varies with the size and contrast of detail in the task, and the retinal illuminance provided by the lighting. The shape of visual performance is a compressive function, in that for a wide range of sizes, contrasts, and retinal illuminances there is little change in performance, but when any of these factors gets low enough, performance deteriorates dramatically. This shape is known as the "plateau and escarpment" of visual performance.

Before considering the impact of daylight on visual performance it is necessary to consider the impact of lighting in general. The first thing to understand about the impact of lighting conditions is evident in Figure 3. This shows the performance of the numerical verification task at different luminance contrasts (Rea, 1981). In this task, two printed pages, the reference page and the response page, each containing a column of 20 five-digit numbers, are used. The five-digit numbers on the reference page are random numbers. The corresponding numbers on the response page are the same except that some of the five-digit numbers differ by one digit. Measurements are made of the time taken to compare the two columns, the number of discrepancies missed (misses), and the number of false discrepancies identified (false positives). In Rea (1981), these measurements were made for a constant illuminance on the printed pages of 278 lx and for a wide range of luminance contrasts for the reference page. Luminance contrast was varied by changing the reflectance of the ink used to print the numbers; by making the ink of either specular or matte reflectance; by changing the geometry between the luminaire providing the illuminance, the numerical verification task and the observer; and by varying the percentage of vertical polarization in the light incident on the numerical verification task. Figure 3 shows the change in the mean time taken, the number of misses, and the number of false positives plotted against luminance contrast. It is evident that for a wide range of luminance contrasts, there is very little change in any of the performance measures. However, as luminance contrast drops below about 0.4, the time taken starts to increase, accelerating as luminance contrast decreases further. A similar pattern can be seen for the misses and false positive data. These data illustrate that both the speed and accuracy of performance deteriorate with reduced visibility in a non-linear manner. They also demonstrate that luminance contrast is a major determinant of task performance, no matter how that luminance contrast is achieved.

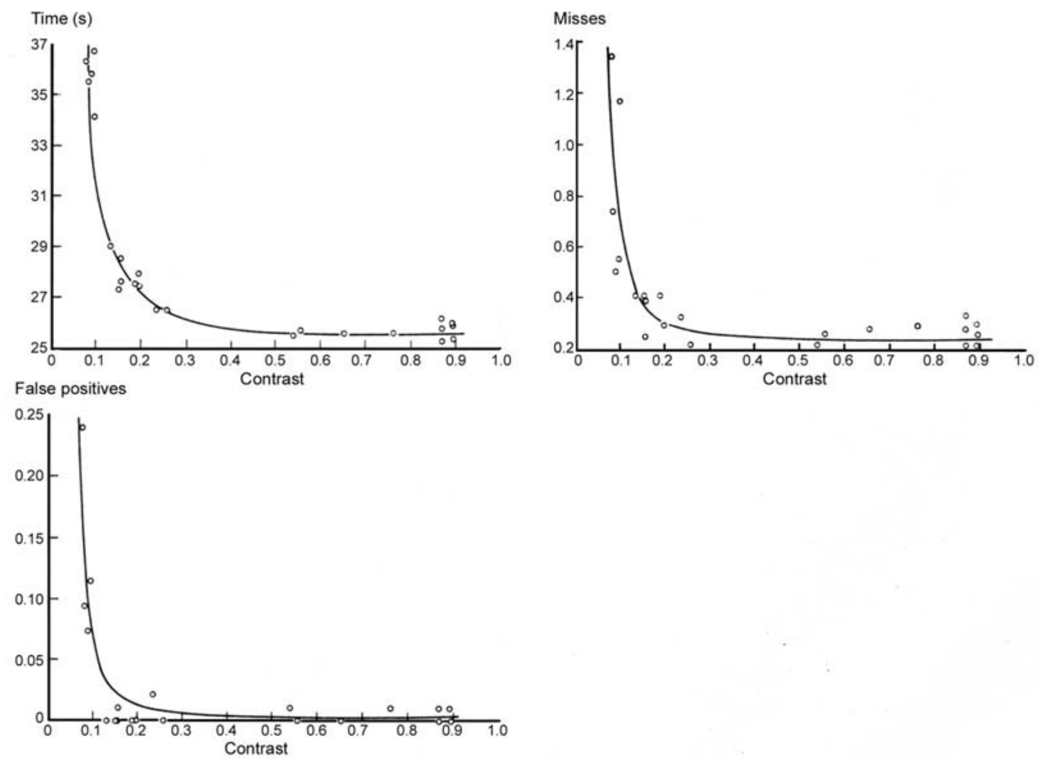

Figure 3: The mean time taken, number of misses, and number of false positives for the numerical verification task, plotted against luminance contrast (Rea, 1981).

Although these data show an effect of task visibility, they do not involve any change in lighting conditions. Fortunately, Rea (1986) provides data that do involve lighting conditions collected from people doing the numerical verification task using the same experimental materials, experimental room, and procedures as in the earlier study (Rea, 1981) for a range of illuminances from 50 lx to 700 lx (giving a range of background luminances from 12 cd/m^2 to 169 cd/m^2) and a range of luminance contrasts from 0.092 to 0.894.

The data on time taken to compare a set of 20 five-digit numbers, the number of misses, and the number of false positives were very similar to those obtained in the earlier study (Rea, 1981) and by others using the numerical verification task (Slater et al., 1983). Figure 4 shows the compressive function with luminance contrast that would be expected from the results in Figure 3 but there are two additional effects of increasing luminance that should be noted. The first is that, at the same luminance contrast, performance is better at higher luminances, for all luminance contrasts. The second is that performance tends to saturate at lower luminance contrasts for higher luminances.

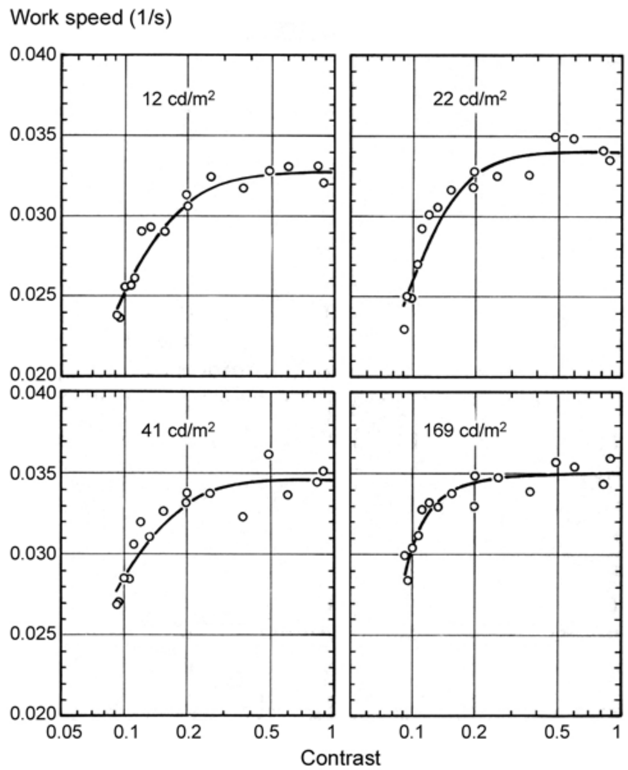

Figure 4: Mean work speed, expressed as the reciprocal of time taken, to perform the numerical verification task, plotted against luminance contrast, for four background luminances (Rea, 1986).

The time taken to compare the reference and response pages used as the basis of Figure 4 is a measure of task performance, in that it includes both visual and non-visual components. To produce a time measure that could reasonably be called a measure of visual performance, Rea subtracted two elements of time from the total time taken. The first was an estimate of the time taken to make a mark against any response page number that contained a discrepancy. The second was the time taken to read the numbers in the response list. The remaining time was then the time taken to read the numbers in the reference list. It is the reciprocal of this time that was taken as a measure of visual performance from which a predictive model of visual performance was developed. Figure 5 shows the form of this model, called the Relative Visual Performance (RVP) model, plotted against background luminance over the range 12 to 169 cd/m^2 and luminance contrast over a range from 0.08 to 1.0. The vertical axis is a relative measure (RVP) calculated from the reciprocal of the time taken to read the reference page, normalized to a value of 1.0 at a background luminance of 169 cd/m^2 and a luminance contrast of 1.0. The shape of this model has been described as the "plateau and escarpment" of visual performance (Boyce and Rea, 1987). Over a wide range of task and lighting variables, the change in relative visual performance is slight, but at some point it will start to deteriorate rapidly. A more elaborate RVP model has been developed on the basis of reaction times, and covers both luminance contrast, and visual size, as well as retinal illumination (Rea and Ouellette, 1988, 1991). This model shows a very similar "plateau and escarpment" shape to that evident in Figure 5 and has superseded the earlier model.

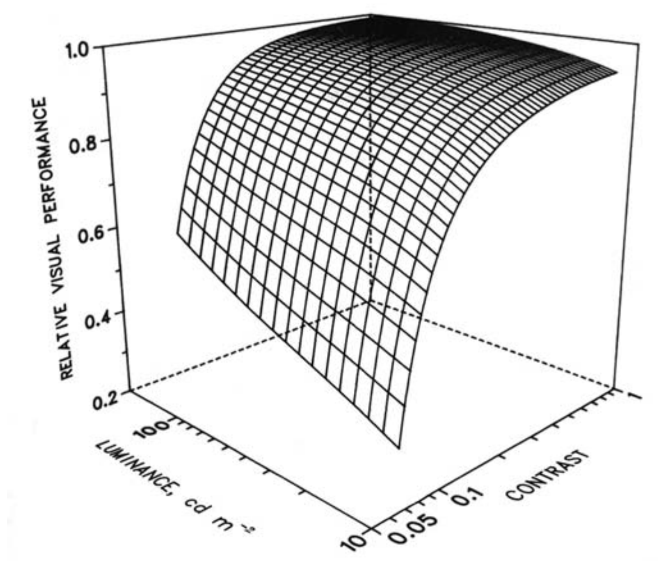

Figure 5: The RVP model of visual performance (Rea, 1986).

The virtues of this RVP model are that it is fully predictive, in that all the quantities needed to predict the level of visual performance of a specific task can be measured, and the predictions thus made have been tested and found to be accurate (Bailey et al., 1993; Eklund et al., 2001). However, the RVP model can only be applied to a limited range of tasks. The tasks for which the RVP model is most suited are those that are dominated by the visual component, that do not require the use of off-axis vision, that present to the visual system stimuli that can be completely characterized by their visual size, luminance contrast, and background luminance, and that have values that fall within the ranges used to develop the model. As for the aspects of lighting considered, the amount of light is covered by the inclusion of retinal illumination in the model, and light distribution is covered by the changes it makes to the luminance contrast both directly, by veiling reflections, or at retinal level, by disability glare. One aspect of lighting that is not considered by the RVP model is light spectrum. Light spectrum can obviously have an effect on the performance of chromatic tasks where the perception of color is an inherent part of the task (Williams, 1966) and where luminance contrasts are low (Eklund, 1999). It has also been argued that using a light spectrum that produces a smaller pupil size will improve retinal image quality and hence visual acuity, which in turn will lead to an improvement in visual performance for achromatic tasks (Berman et al., 1993, 1994). However, recent work has shown that this is only true for tasks close to visual threshold (Boyce et al., 2003). There is still much to learn about the effect of lighting conditions on visual performance but the basic compressive shape of visual performance is well understood. Among the topics that require further study are how lighting affects the performance of tasks requiring the application of off-axis vision, e.g., visual search, and whether performance starts to decline for high contrast and high luminance conditions when a task with a strong pattern is used (Wilkins, 1995)

3.3 Daylight and visual performance through the visual system

Synopsis: Physically and physiologically, daylight is just one more light source. How daylight influences visual performance depends on how it is delivered. Either good task performance or poor task performance can be expected depending on the amount of daylight delivered and whether glare, shadows, or veiling reflections are produced.

Having examined what is known about the relationship between the lighting conditions and visual performance, it is now necessary to consider the potential role of daylight and daylighting in modifying visual performance. The first question to consider is whether there is anything about daylight, *per se*, that makes it superior to all other light sources. This question can be considered at two levels, the physical and the physiological. Physically, daylight is simply electromagnetic radiation in the wavelength range that is absorbed by the photoreceptors of the human eye. In this respect it is the same as all other light sources. The actual wavelengths present in daylight will vary over the day, with meteorological conditions, with latitude, and with season. It is this variability in spectral content and the fact that, at all times, it is a continuous spectrum with elements in all parts of the visible wavelength range, that separates daylight from several of the more widely used electric light sources, such as the fluorescent lamp used in nearly all commercial buildings and the metal-halide lamp used in many industrial buildings. There are electric light sources available, such as the xenon lamp and some filtered incandescent lamps, which have a spectral content similar to that of daylight on some occasions, but there are none that also show the variability in spectrum over time.

Physiologically, the response of the human visual system to the incident light spectrum is determined by the spectral sensitivity of the three types of cone photoreceptors and the one type of rod photoreceptor in the retina of the human eye. All these photoreceptors have a broad spectral response; i.e., the response of each photoreceptor type covers a wide range of wavelengths and overlaps the others to some extent. This implies that the visual system should not be very sensitive to the exact spectral content of the light and should be capable of functioning equally well using light consisting of many different wavelength combinations. This belief is supported by measurements of visual acuity, contrast sensitivity, and other threshold visual functions made under different light sources (Boff and Lincoln, 1988, Berman et al., 1993, 1994). These measurements show small effects of light spectrum that disappear in suprathreshold conditions. The only aspects of task performance that are strongly influenced by the spectral content of the illuminant in both threshold and suprathreshold conditions are color naming and color discrimination; a fact that is not unexpected given that changes in the spectral content of the illuminant will change the stimulus presented to the visual system and the state of adaptation of the visual system. Again, the obvious conclusion is that daylight, *per se*, is not inherently superior to other light sources as regards a stimulus to the visual system.

Given that daylight, *per se*, is not inherently superior to other light sources as a stimulus to the visual system, there is still the question of how good daylighting is as a method of lighting a space to achieve a high level of visual performance. The answer is that daylighting is as good as the architect who designs it. Lighting in a space can be considered on three dimensions; the amount, the spectrum, and the distribution of light. Daylight will almost always have a good light spectrum, in the sense that it has a high CIE General Color Rendering Index. The only exception to this occurs where the interior surfaces from which daylight is reflected or the glass through which daylight is transmitted are highly saturated in chroma so that the spectrum is distorted. As for the amount and distribution of daylight, these two dimensions can vary widely depending on how the daylight is delivered. Well-designed daylighting will deliver copious amounts of light, without either discomfort or disability glare, free from strong shadows and veiling reflections. Poorly designed daylighting will deliver either inadequate amounts of light, so that electric lighting has to be used, or copious amounts of light together with discomfort and disability glare, as well as strong shadows and veiling reflections. One aspect of daylight delivered through windows that consistently separates it from ceiling-mounted electric lighting is the greater amount of light delivered to vertical surfaces, and high illuminances on vertical surfaces are associated with increased preference and a reduced sense of gloom (Shepherd et al., 1992). From this discussion it should be apparent that daylighting is the same as any other form of lighting. It has the potential to be either good or bad depending on how it is done.

Given the above, it would be expected that when people are asked to do achromatic visual work there would be little difference in the performance of that work under daylight or electric light, as long as both provide the same amount and distribution of light. Santamaria and Bennett (1981) carried out just such an experiment using daylight and cool white fluorescent lamps as light sources. The distribution of light and the amount were controlled to be the same for the two light sources. Further, the light sources were hidden so the subjects were unaware of which light source was in use. The tasks done were threading needles, proofreading text, and reading graphs. All three tasks were considered by the subjects to be visually easy. No statistically significant differences in performance for the different light sources were found for the needle threading or the graph reading, but there was a small but statistically significant difference between daylight and the fluorescent light for the proofreading ($p<0.05$), the proofreading being performed 5 percent faster under daylight than under the fluorescent light. Such a difference is understandable because the fluorescent lighting was operating from an alternating current electricity supply and this produces regular fluctuations in light output at twice the supply frequency. Such fluctuations in luminance have been shown to modify saccadic eye movement patterns while reading (Wilkins, 1995).

Santamaria and Bennett (1981) conclude that for everyday visual tasks, there is little difference in performance between daylight and fluorescent light when such aspects as the amount and distribution of light are controlled. Of course, this conclusion does not hold for tasks involving fine color discrimination, because then light spectrum is important. For fine color discrimination, as is required in the grading of cotton and the matching of textiles, a high illuminance and daylight, or electric lighting with a spectrum close to some form of daylight, are recommended (Nickerson, 1948; ASTM, 1996a and b). Another situation in which light spectrum is important is the performance of achromatic near-threshold tasks (Berman et al., 1993, 1994), although it is necessary to appreciate that close to threshold even very small changes in visibility are important for visual performance.

Two conclusions can be drawn from this discussion of daylight and visual performance. The first is that daylight is not inherently superior to all other light sources for all tasks. The second is that the benefits of using daylight for visual performance is a matter of probability. Benefits in visual performance are more likely to be found when the task involves fine color discrimination and the daylight is delivered at a high level without glare or any reduction in task visibility caused by veiling reflections or shadows. Benefits in visual performance are unlikely to be found where the task is achromatic and visually easy. Decrements in visual performance are likely when the daylight is delivered in such a way that the task visibility is reduced, either because the amount of light on the task is inadequate, or glare, or veiling reflections, or strong shadows are present.

3.4 Human performance and the circadian system

Synopsis: The circadian system sets the "platform" from which humans operate to perform all activities. The daily light - dark cycle is one of the most potent stimuli for entraining the circadian system. Exposure to light

during the circadian night can phase shift the circadian cycle and increase alertness. Performance during the circadian night is worse than during the circadian day because of temporary lapses of attention.

Circadian rhythms are a basic part of life and can be found in virtually all plants and animals, including humans. The role of circadian systems is to establish an internal representation of external night and day. This internal representation is not just a passive response to external conditions but rather is predictive of external conditions to come. The human circadian system involves three components; an internal (endogenous) oscillator, located in the suprachiasmatic nuclei; a number of external (exogenous) oscillators that can reset (entrain) the internal oscillator, and a messenger hormone, melatonin, that carries the internal "time" information to all parts of the body through the bloodstream. In the absence of light, and other cues, the internal oscillator continues to operate but with a period longer than twenty-four hours. External stimuli are necessary to entrain the internal oscillator to a twenty-four hour period and to adjust for the seasons. The light - dark cycle between day and night is one of the most potent of the external stimuli used for entrainment.

Unfortunately, not everybody is able to work during the circadian day. A significant minority of workers are shift workers who are active at night and hence may be trying to work while their body is in circadian night. It is interesting to consider what the effect of this situation is on task performance. The first thing to say is that the effect of trying to work in the circadian night can affect all types of task, not just visual tasks. This is because the circadian system affects the "platform" from which we operate and consequently affects all parts of the brain and body. Tilley et al. (1982) studied the sleep patterns and performance of shift workers operating a weekly, alternating, three-shift system. Workers doing night shift, who had to sleep during the day, had shorter duration sleep of degraded quality. As for performance, both simple reaction time and four-choice reaction time were both longer during night shift relative to day and afternoon shift and tended to show a deterioration over the number of days on shift, probably because of the accumulation of sleep debt caused by the inferior sleep duration and sleep quality during the day. Cajochen et al. (1999) studied the sleep and performance patterns of people kept awake for 32 hours; i.e., a period covering a conventional day, starting at 08:00 hours and extending to 16:00 hours the next day. Figure 6 shows the patterns in core body temperature and plasma melatonin, both well-established circadian rhythms; eye blink rate, slow eye movements and stage 1 EEG patterns, and ratings on the Karolinska sleepiness scale, all of which are related to sleep; and performance on a reaction time task, a mental arithmetic task and a short-term memory task. It is important to note that during the 32 hours of wakefulness, the subjects were exposed to a constant illuminance of 15 lx; i.e., there was no light - dark cycle in this study. Figure 6 shows the expected circadian pattern of decreased core body temperature and increased plasma melatonin at night. The sleep measures all show an increased propensity to sleep during the night with some recovery the next day. The performance measures all show a decrement in performance over the night with some recovery the following day, although not enough to recover to the level of performance achieved at the beginning of the trial. Of particular interest are the results on the reaction time task. What is evident in these data is the increase in range in reaction times at night. The 10 per cent fastest reaction times at night are similar to what they are during the day but the 10 per cent slowest are 20 times slower. This spread in reaction times is consistent with one of the most commonly observed effects of continuous work without sleep, the presence of periods of no response or lapses (Wilkinson, 1969). There are a number of task characteristics that determine the likelihood of lapses occurring. Tasks which are of long duration (i.e., more than 30 minutes), monotonous, and externally paced seem to be more likely to show lapses during sleep deprivation. Conversely, tasks which are considered of short duration, interesting, or rewarding, and which are self-paced are less likely to show lapses, although the self-paced task may be done more slowly to maintain the same level of accuracy (Froberg, 1985). It is important to realize that the change in the number of lapses is relative. All tasks show some decline with increasing sleep deprivation, but the decline is less for the short-duration, interesting, rewarding, self-paced tasks.

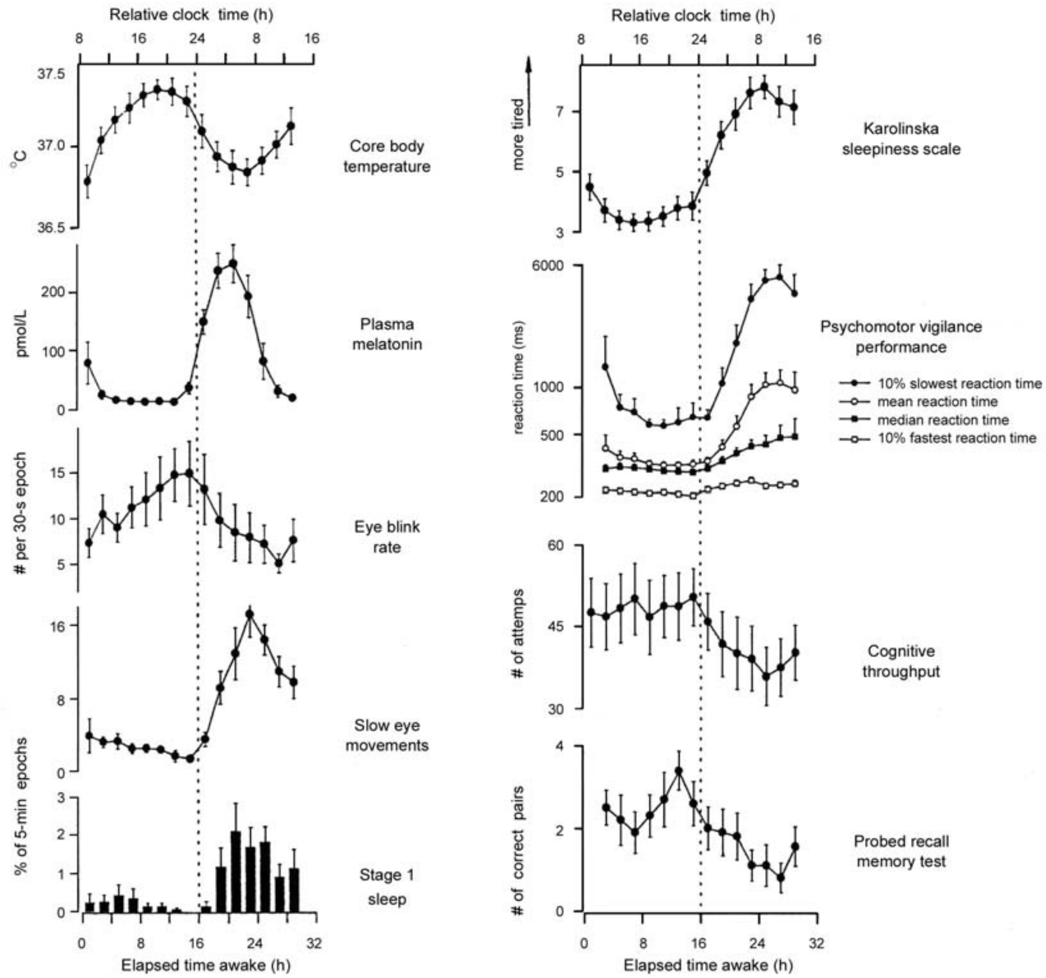

Figure 6: The time courses of core body temperature and melatonin concentration over 32 hours. Time courses of measures of sleepiness over 32 hours. Time courses of task performance for highly visible tasks requiring vigilance, mental arithmetic, and short-term memory over 32 hours. The dotted vertical line represents the subjects' habitual bedtime. The error bars are standard errors of the mean (Cajochen et al., 1999).

One aspect of task structure of particular interest is the extent to which short-term memory is required. Tasks requiring the use of short-term memory seem particularly sensitive to sleep deprivation, an observation consistent with the finding of Cajochen et al. (1999) that the frontal areas of the brain, which are associated with short-term memory, are more susceptible to sleep loss than occipital areas.

3.5 Daylight and the circadian system

Synopsis: Exposure to daylight outdoors is usually the major factor in

determining the phase of the circadian rhythm. Daylight outdoors delivers a high illuminance at the eye that is better matched to the spectral sensitivity of the circadian system than most electric light sources.

As the adverse effects on performance shown in Figure 6 are all associated with working at night, it might be wondered how daylight can improve the situation given that, by definition, night involves the absence of daylight. The answer is that exposure to daylight is a very potent means of providing enough light to entrain the circadian system. This is evident in a study by Eastman et al. (1994), who examined the shift in circadian phase caused by exposure to light at night and the wearing of dark welder's goggles during the day, combined in all possible ways. This meant that some subjects were exposed to 5,000 lx illumination at night but were free to travel home in daylight without wearing the goggles. Others were exposed to less than 500 lx at night but wore the dark welder's goggles during the journey home. Yet others were exposed to 5,000 lx at night and wore the welder's goggles on the journey home, while yet others were exposed to less than 500 lx at night but did not wear the goggles travelling home. Receiving 5,000 lx at night and wearing the goggles during the day gave the greatest phase shift; either factor alone gave some shift, while neither rarely produced any phase shift. This result emphasizes three points. The first is that illuminances typical of conventional interior lighting can produce phase shifts, (i.e., 500 lx during the night), provided exposure to daylight is limited. The second is that to guarantee a phase shift, it is necessary to control light exposure throughout the 24-hour period. The third is that exposure to daylight will often be the dominant factor in determining the phase of the circadian system and hence whether people are being asked to work in circadian night.

The reason why exposure to daylight is important is that it usually produces a high illuminance at the eye. Further, the spectrum of daylight is better matched to the spectral sensitivity of the human circadian system, which shows a peak sensitivity at about 465 nm (Brainard et al., 2001; Thapan et al., 2001), than commonly used electric light sources, such as incandescent, fluorescent, or high-pressure sodium lamps. This is not to say that sufficient retinal illumination to entrain the circadian system cannot be provided by electric lighting, it is simply to say that it is less likely. Exactly how much light exposure is sufficient to entrain the human circadian system depends on the amount of light, the spectrum of the light, and the duration of exposure. Zeitzer et al. (2000) established a dose-response relationship for light exposure from Cool White fluorescent lamps, using the phase shifting and suppression of melatonin as markers of the state of the circadian system. The illuminances at the eye during the light exposure ranged from 3 to 9,100 lx. Figure 7 shows the phase shift in melatonin concentration plotted against illuminance at the eye. The phase shift is delayed, as would be expected from the timing of the light exposure but, more interestingly, the phase shift saturates, i.e., reaches 90 percent of the asymptotic maximum, at an illuminance at the eye of 550 lx while the half-saturation response is produced by an illuminance of about 100 lx.

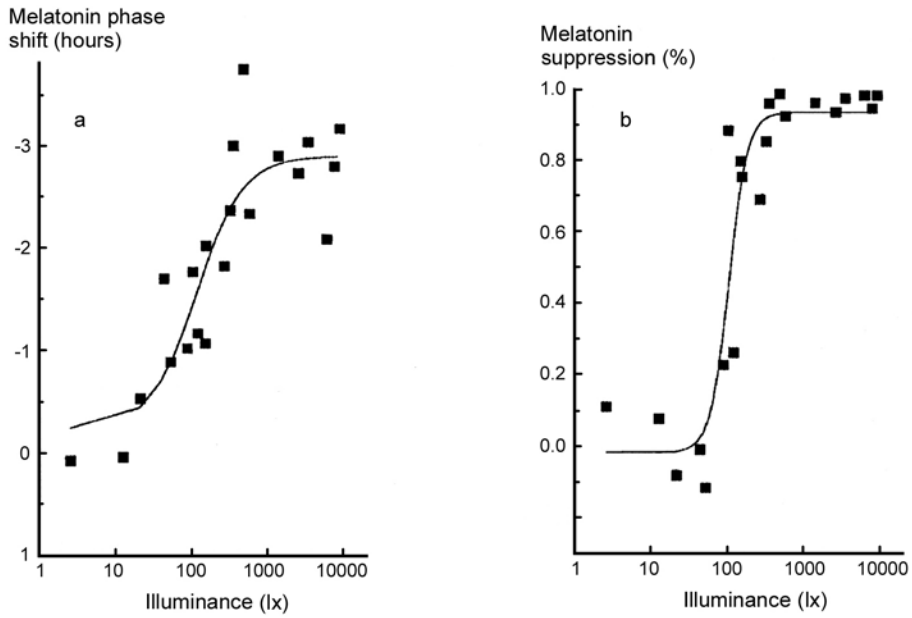

Figure 7: The effect of illuminance at the eye on a) melatonin phase shift and b) percentage melatonin suppression, for 6.5 hours of light exposure centered 3.5 hours before the core body temperature minimum (Zeitzer et al., 2000).

Figure 7 also shows the percentage reduction in melatonin concentration during six and one half hours exposure to different illuminances at the eye. For melatonin suppression, saturation of suppression occurs at about 200 lx and the half-saturation occurs around 100 lx. Similar results have been found by Brainard et al. (1988). Yet others have shown that, given an exposure time of several hours, illuminances of the same order as those found in conventional lighting installations can delay the onset time for melatonin (Wehr et al., 1995), have an acute effect on alertness (Cajochen et al., 2000), and phase shift the sleep-wake cycle (Boivin and James, 2002).

Taken together, these results imply that the dose-response relationship for the effect of light on the circadian system follows a compressive, non-linear function. Further, they imply that, given a long enough exposure time, illuminances that occur in everyday electric lighting installations can be enough to entrain the human circadian system and may be the main source of entrainment for populations in northern climates where daylight is limited for long periods and to many who live in urban areas, with limited exposure to daylight. Nonetheless, where daylight is available, there can be little doubt that exposure to it will be beneficial in terms of keeping the circadian system properly entrained. It is also important to note that for most ceiling-mounted electric lighting systems, the illuminance at the eye will be markedly lower than the illuminance measured on the horizontal working plane that is conventionally used in lighting design, but this is not the case for daylight provided through a window.

But does inaccurate entrainment of the circadian system have any effect on task performance? Clearly it does if misalignment of the circadian system is enough to make people work during their circadian night (French et al., 1990; Boyce et al., 1997). It has also been suggested that misalignment of the circadian system can cause changes in behavior at work. Figueiro et al. (2002) made observations of the activities undertaken by workers in a software development company in upstate New York. All the workers examined had similar work functions, but some of them were in windowless offices and some were in windowed offices. The study was done in winter when the exposure to daylight before or after work was limited. It was hypothesized that the people in the windowless offices would not receive sufficient light to entrain their circadian systems and so would seek to entrain them either by seeking out exposure to daylight and consequently spending less time in their offices, or by seeking more social interactions, a factor that can also be used to entrain the circadian system (Schaap and Meijer (2001). No statistically significant differences were found in the occupancy of the windowed and windowless offices, but the workers in the windowless offices did spend a small but statistically significantly greater amount of time talking to others, either directly or by telephone; and a small but statistically significantly lesser amount of time working on their computer, relative to the workers in the windowed offices. Of course, an alternative explanation for these findings would be that the workers in the windowless offices were seeking additional short-term stimulation, something that was provided by the view out in the windowed offices, and the differences in behavior had nothing to do with the circadian system. As suggested by the authors, one way to test this possibility would be to repeat the test in summer, when daylight is available to all, before and after work, in which case the differences in behavior would be expected to disappear if they are based on the circadian system but remain if they are due to the desire for short-term stimulation. Regardless of which explanation is correct, the presence of a window would seem to provide a benefit in terms of desirable behavior at work.

3.6 Human performance and the perceptual system.

Synopsis: Changes in mood change people's judgements and behavior at work. Lighting conditions can change people's moods. However, there is little stability in mood change for the same lighting conditions. For the same lighting conditions, the direction and magnitude of mood change will vary with an individual's discomfort, preferences, expectations, and gender.

Strictly, to determine that an effect of lighting on task performance is operating through the perceptual system and not the visual system, it is necessary to separate changes in mood from changes in visibility. One way to solve this problem is to vary the lighting of the room but not in the immediate task area, and to use tasks that are highly visible so that changes in visibility will make very little difference to visual performance. One study where this was done showed that very different electric light distributions in a windowless room had no effect on sustained task performance, despite the light distributions being considered very different in quality by lighting experts (Eklund et al., 2000). This demonstrates the difficulty in making a direct link between lighting conditions and human performance through mood. The basic problem is that mood is subject to so many influences that the impact of any one alone is likely to be masked by uncontrolled variation in the others. What this suggests is that the best that can be done to examine the effect of lighting on task performance through the perceptual system is to determine the plausibility of each step separately.

The first step is to consider whether lighting conditions can change the mood of people in the lit space. There is little doubt that they can. A number of studies using electric lighting have shown that differences in the illuminance provided and the color properties of the illuminant can alter the mood of people temporarily occupying the space (Baron et al., 1992; Knez, 1995, 2001; McCloughan et al., 1999). The problem with these results is that the direction of the change in mood is not consistent with lighting conditions and there are gender differences in changes in mood. This variability in mood change emphasizes the point that changes in mood are influenced by several factors other than the condition being experienced at the time. One such factor is how different the conditions being experienced are from the conditions preferred. Newsham and Veitch (2001) examined the mood of people who worked for eight hours in a windowless office with a fixed illuminance. At the end of the eight hours, the subject was offered the chance to adjust the lighting to his/her preferred condition. They found that the further the fixed lighting was from the subject's preferred condition, the more negative was the subject's mood over the day. Another factor is the subject's expectations about the lighting. Purcell and Nasar (1992) suggest that mood changes can be generally explained by the magnitude of discrepancies between the subjects' expectations and the reality. When there is no discrepancy, there is no mood change. When the discrepancy is minor, there is generally a positive mood change, but as the magnitude of the discrepancy increases, the probability of a negative mood change increases. This concept indicates the importance of knowing what a subject's expectations are for the lighting of the space. Finally, there is the factor of the length of time for which the subject has been exposed to the condition. In all the experiments discussed above, the exposure was short, usually a matter of minutes rather than days, months, or years. Kuller (1991) proposed that mood changes associated with the physical environment could be divided into a short-term phasic response and a long-term tonic response involving habituation. The studies discussed above can be considered studies of the short-term phasic response. If habituation occurs following long-term exposure, then it would be predicted that mood changes on entering the space would become less and less, as the conditions became the norm; i.e., the subject's expectations are reset to the prevailing conditions.

Assuming that mood can be changed systematically, what are the effects on human performance? Mood has been shown to influence cognition and social behavior. Specifically, a more positive mood has been shown to increase efficiency in making some types of decisions, and to promote innovation and creative problem-solving. It also changes the choices people make and the judgments they deliver. For example, it has been shown to alter people's preferences for resolving conflict by collaboration rather than avoidance and also to change their opinions of the tasks they perform (Isen and Baron, 1991). A negative mood has the opposite effects.

3.7 Daylight and the perceptual system

Synopsis: Daylight is clearly preferred over electric lighting as a source of illumination. Windows are valued particularly for the daylight they deliver and the view out they provide. Windowless spaces are generally disliked, particularly where the space is small and there is little stimulation available. Given this clear preference for daylight, it might be thought that the presence of windows would improve mood, but this has been hard to demonstrate. Further, it is easy to observe that people will give up daylight when it is associated with visual or thermal discomfort or a loss of privacy.

There is no doubt that different forms of electric lighting can change the mood of people working in a space, at least over a short time period, so the obvious question to consider is what is the effect of daylight on mood? There is no doubt that people prefer daylight over electric lighting as their primary source of illumination. Wells (1967), Manning (1967), and Markus (1967) in the UK; Heerwagen and Heerwagen (1986) in the USA; Veitch (1993) in Canada, and Cuttle (2002) in the UK and New Zealand, have all shown that high percentages of survey respondents prefer to work by daylight. These findings are exemplified by Table 1, from Heerwagen and Heerwagen (1986), which shows the percentages of occupants of offices thinking that daylight or electric light is better for seven different purposes. Daylight is considered better than electric lighting, which presumably means fluorescent lighting, for all seven purposes, although, interestingly enough, the difference is less for work performance and for jobs requiring fine observation. Very few people had no opinion on this. This

Table 1: Percentage of occupants preferring daylight or electric light for different factors

Factor	Daylight better	Electric lighting better	No difference	No opinion
For psychological comfort	88	3	3	6
For office appearance and	79	0	18	3

pleasantness				
For general health	73	3	15	8
For visual health	73	9	9	9
For color appearance of people and furnishings	70	9	9	12
For work performance	49	21	27	3
For jobs requiring fine observation	46	30	18	6

persistent trend of preference for daylight is consistent with the finding that people prefer to sit by windows (Markus, 1967; Aldworth and Bridgers, 1971; Collins 1975; Ludlow, 1976; Heerwagen and Heerwagen, 1986; and Cuttle, 2002).

But what is it that makes windows so attractive? One answer is that windows provide something that people crave. Windows can provide daylight, sunlight, ventilation, and noise into the occupied space, and a view out from the occupied space. They also allow access to information about the passage of time and weather conditions, both of which involve an inherent and meaningful variability. The results of surveys of office workers suggest that of this list, the two most important attributes of windows are the view out and the admission of daylight (Collins, 1975; Brill, 1985). The importance of a view out is demonstrated by the work of Young and Berry (1979). They examined people's preference for an office with either a real window, providing both a view out and daylight in the office, or an artificial window showing a dynamic view of nature but providing very little light into the office. There was very little difference in the preferences for the two window types, implying that it is the view that is dominating the preference.

An alternative answer is that windows are preferred by default, because people have a negative view of electric lighting. This view is consistent with the results reported by Cuttle (2002). From a series of questionnaire surveys of office workers in England and New Zealand, he concluded that the preference for daylight could be attributed to the belief that working by daylight results in less stress and discomfort than working by electric light. The belief was not so much that daylight was beneficial, but rather that working by electric lighting was detrimental to health, particularly in the long term. Of course, this may have been due to the specific forms of electric lighting used in the offices surveyed, which may have been visually uncomfortable, but it is interesting to realize that similar beliefs about the negative effects of fluorescent lamps on people were found in a survey of 2,950 members of the public attending a New York State Fair in 1991 (Beckstead and Boyce, 1992). A bias against some widely used forms of electric lighting can be expected to produce a desire for daylight, some form of lighting being essential and daylight being the most obvious alternative.

Regardless of which of these answers is correct, and both may be, the next step is examine whether having windows is associated with changes in mood. This has been surprisingly difficult to demonstrate. Neither Hartleb (1989) nor Gutkowski (1992) were able to show differences in mood in people briefly exposed to small rooms with and without windows. This may have been because they only measured mood once for each exposure, so it is possible that differences in mood due to the presence or absence of windows were masked by pre-existing differences in mood. Dasgupta (2003) measured mood at the start and end of the exposure period. She was able to show a small but statistically significant reduction in negative mood for people working for about 20 minutes in a private office with a large window, during daytime; but no change in negative mood for the same people, in the same office, at night.

If the presence of windows does reduce negative mood, it would be hypothesized that this would result in an improvement in task performance. Some researchers have tested this hypothesis. Hedge (1994) measured the performance of a clerical task on a computer in a room lit by different electric lighting systems, with and without windows. He found a small but statistically significant improvement in task performance when windows were present. Whether this occurred because the presence of windows improved the stimuli the tasks presented to the visual system, or changed the operating state of the visual system, or because the subjects were in a better mood, or whether the rapid fluctuation of light output of the fluorescent lighting caused discomfort, or if all of these effects occurred, is not clear. Stone and Irvine (1991) also measured the performance of a managerial task in a room which had a window or was windowless. In this case, no statistically significant effects of having a window were found for task performance or mood.

The difficulty experienced in demonstrating that the presence of windows improves mood and hence task performance carries two implications. The first is that if windows do have such an effect, it is small relative to all the other factors that influence mood. The second is that any effects of windows on mood may be short-lived. This latter implication is consistent with the short-term phasic response and the long-term tonic response to environmental conditions proposed by Kuller (1991). The experiments discussed above are tests of the short-term phasic effect of windows. One study in which a long-term tonic response to the presence of windows is implied is that of Wilkins et al. (1989). In this study, it was shown that the occupants of offices that overlooked a six storey light well suffered more headaches the lower the office was within the well and thus the less the amount of daylight. Repeated headaches experienced at work are not likely to do much for an individual's mood. It is also interesting to note that the view out on all floors was almost constant, it being of the offices on the opposite side of the light well.

Studies of the differences in mood between people who have inhabited windowed and windowless spaces for a long time can also be considered studies of the long-term tonic effect. Unfortunately, these studies have also produced mixed results. Surveys of the occupants of windowless offices have shown that when the space is small and the occupant has little opportunity to leave the space, the occupants are less satisfied with their jobs and with the physical environment (Finnegan and Solomon (1981); and the lack of variety is noticeable and the lack of windows is disliked (Ruys, 1970). However, in large spaces, such as school classrooms (Larson 1973) and factories (Pritchard, 1964), the lack of windows has a much more variable impact. This may be because in a large space, where there are many other activities going on and there is a lot of interaction between people, there is often plenty of stimulation in the environment. In a small office, it may be that the view out of the window is the only source of environmental stimulation. Some support for this view comes from the work of Heerwagen and Orians (1986). They observed that people occupying small private offices without windows used twice the number of visual materials to decorate their offices as did people whose offices had windows. Overall, the work on people's reactions to windowless buildings supports the idea that a view out is valued, but it does not necessarily support the primacy of view out over the provision of daylight. In windowless offices, surrogate daylight is provided by the electric lighting; it is a surrogate view that is missing.

The above pattern of results is consistent with the view that daylight and a view out are nice to have but not essential, as long as there is good electric lighting and plenty of stimulation. Some support for this view comes from observations of almost any multi-story office building. Such observations will reveal that people are willing to give up daylight when it also causes visual and thermal discomfort, or leads to a loss of privacy, and not just for a short time. Measurements of the use of window blinds in multi-story office buildings have shown two trends. The first is that window blinds are most likely to be closed on ground floors where there are many passers-by, and, on all floors, as the sun begins to shine on the window and so cause solar glare and radiant heating (Maniccia et al., 1999). This might be expected. Less expected is the second trend, that many of these blinds are kept closed even after the sun has ceased to shine directly on the window; and that, in some cases, the blinds are left closed for days, months, or years (Rea, 1984). Further, if daylight, *per se*, is strongly desired, it might be expected that when there is plenty of daylight available in a space, people will switch off or dim the electric lighting to minimize its impact on the daylighting. However, prolonged measurements in a set of deep, private offices with large windows have shown that, given the opportunity, people tend to increase the amount of electric light as the amount of daylight in the office increases (Begemann et al., 1994, 1995). This behavior is consistent with a desire to balance the luminance of the window and the surfaces near it with the luminances of the surfaces deep in the room. It also implies that the overall pattern of light distribution in the room is more important than the purity of daylight. This lack of concern with the absolute purity of daylight is again evident in the widespread use of tinted glazing in buildings and the wearing of tinted sunglasses by people outdoors.

So why are daylight and a view out so desired? The observations above suggest that one reason why daylight is so popular as a means of lighting is that, if carefully designed, daylight delivered through windows provides a comprehensive package which can meet the requirements of good lighting by revealing both the task and the space clearly and the requirement of environmental stimulation by variation of lighting conditions in the space and a view out through the window. By comparison, electric lighting installations, if well designed, can provide good visibility of the task but often do little for the space and rarely provide any variation over time or space. Even when electric lighting installations are designed to produce some variation over time and space, the variation is usually simple, repetitive, and arbitrary compared to the complexity of daylight variation and the meanings that such variations carry. But the desire for daylight is not unlimited. When daylight through windows is inappropriate, either because it causes visual or thermal discomfort or because of excessive environmental stimulation, or because of loss of privacy, it is common to restrict daylight in some way. This is evident in a study by Maniccia et al. (1999) of occupants' use of window blinds and electric lighting controls in private offices. They found that window blinds were adjusted so as to occlude direct sunlight but to allow skylight to enter the office and to preserve a view out; i.e., to eliminate the source of discomfort while preserving the desirable attributes of windows.

As for why a view out is desired, this too can be explained by the desire for meaningful stimulation, but it might also be due to biophilia. Biophilia is a belief that there is an innate emotional affiliation of human beings to other living things, both plant and animal (Kellert and Wilson, 1993). This affiliation is demonstrated by the consistency of our psychological responses to animals and landscapes (White and Heerwagen, 1998), and by the widespread use in indoor planting (Baker, 2000). What this implies is that we have an innate desire to be in contact with nature. Windows provide a means for doing this while at work. Support for the desire for some contact with nature is offered by Heerwagen and Orians (1986), who found that people occupying small windowless offices were much more likely to have pictures of natural scenes on their wall than were people with easy access to windows; by Clearwater and Coss (1991), who found that photographs of distant landscapes were preferred by people in isolated and confined settings such as a mock-up of the space station and a research station in

Antarctica; and by Christoffersen et al. (1999) who found that satisfaction with the view from an office was greater for natural scenes than for man-made scenes.

The main conclusion to be drawn from this discussion of the impact of daylight on human performance operating through the perceptual system is that, while daylight and a view out are undoubtedly desired by the majority of people at their workplaces, the impact of having daylight and a view out on task performance is quite variable. This is for two reasons. The first is that the way in which having daylight and a view out modifies mood is also variable. In some studies, access to windows reduces negative mood and in others, it has no effect. This variable impact is probably due to previous experience and hence expectations. What this means is that different subjects can be expected to show different changes in mood depending on previous experiences of lighting. The second reason for the variable link with task performance is that having daylight and a view out are not always an unalloyed joy. The windows that provide daylight and a view out can also be sources of visual and thermal discomfort, and represent a loss of privacy. It is clear that providing daylight and a view out, while often desired, is not a panacea for good task performance, but then, neither is electric lighting. For both daylighting and electric lighting, the success of an installation all depends on how it is done.

3.8 Daylight and productivity at the organizational level

So far this consideration of the relationship between daylight and productivity has been based at the level of the individual, starting with lighting, moving through individual human performance and assuming that aggregating improvements of individual performance will lead to increased productivity for the organization. However, there is another field of study that proceeds in the other direction; i.e., that starts with the productivity of organizations and examines what factors are influential in determining it, including the physical environment which itself includes lighting.

3.8.1 Happy workers / productive workers

Synopsis: It is widely believed that a happy worker is a productive worker but there is little support for this view. Studies of what it means to be a happy worker have suggested that the important factor is emotional well-being rather than cognitive job satisfaction. There is also argument about whether a feeling of well-being comes from the worker's long term disposition or short-term mood. This distinction is important because daylight and a view out through a window can be expected to alter short-term mood but not the worker's disposition.

One of the most persistent hypotheses in the field of organizational productivity is that a happy worker is a productive worker. This hypothesis can be found in the business management and industrial psychology literature from the era of the Hawthorne studies in the 1920's and 30's to today (Katzell et al., 1975;

Cropanzano and Wright, 2001). While anecdotally supported, this hypothesis has been hard to verify. Researchers in this field have surveyed hundreds of studies over several decades, and their major finding is that the link between job satisfaction and productivity may or may not exist, depending on how these terms are operationalized (Brayfield and Crockett, 1955; Iaffaldano and Muchinsky, 1985; Wright and Cropanzano, 1997; Wright and Staw, 1999a and b). Some component of satisfaction, well-being, or positive affect does indeed often correlate with some kinds of productivity—though findings are not usually able to support a causal link. In fact, some feel that productivity causes satisfaction, not the other way around (Ruch and Hershauer, 1975; Bardo and Ross, 1982).

Typical of research trends up to the 1990s, Ruch and Hershauer (1975) surveyed the attitudes of workers in highly repetitive jobs (electronics assembly and data processing). They attempted to find correlations between attitudes, employee output, and absenteeism. Many correlations between individual attitudes and performance were found, but among different firms, no overall pattern was discerned. In fact, the researchers found mostly negative correlations between attitude and output—in direct contradiction of the happy/productive worker hypothesis. They also found positive correlations between absenteeism and attitude; the more positive the workers' attitudes, the more likely they were to miss time at work. These somewhat puzzling results indicate the difficulty of supporting the happy worker / productive worker hypothesis.

More recent research has concentrated on exploring what it means to be a happy worker. Specifically, it has been established that psychological well-being, rather than job satisfaction, correlates with measures of job performance. This distinction is important. Job satisfaction is considered to be a cognitive assessment of attitude, while psychological well-being is an emotional response (Wright and Cropanzano, 1997; Organ, 1988). In other words, people *think* that they are satisfied or unsatisfied with their jobs, but they *feel* happy or unhappy about their jobs. The failure to find the clear link between job satisfaction and performance may be because, as Wright and Cropanzano (2000) put it, "…job satisfaction scales typically do not contain any items that directly assess happiness." There is also a question of time scale in job satisfaction and psychological well-being. Job satisfaction is a long-term attitude, but psychological well-being is short-term emotional state that may be more amenable to change. It should be easier to induce feelings of well-being at work than to change an overall attitude. For example, if employees feel happiness when they look out of a window or sit in sunshine, that feeling may contribute to their performance on that day while not affecting how they feel about their co-workers, pay, or responsibilities.

Wright and Cropanzano (2000) explicitly set out to determine which construct, job satisfaction or well-being, best predicted performance. In their first study, they found no statistically significant correlation between job satisfaction and performance and no statistically significant correlation between job satisfaction and well-being, but they did find a small but statistically significant correlation between well-being and performance (r = 0.33). Their second study checked whether well-being influenced performance over time. Again, they found no relationship between job satisfaction and performance but did find the measure of well-being predicted performance ratings.

The next question that must be resolved is whether the feelings of well-being that affect performance are stable or transient. This distinction can also be thought of as the difference between long term “disposition” and short term “mood.” In some studies, performance was correlated with feelings at the moment, i.e., mood, rather than prolonged feelings, i.e., disposition (Wright and Staw, 1999a). From this we might infer that momentary or day-to-day lifts in mood resulting from a window view or enjoyment of sunlight could have effects on productivity. For example, Wright and Staw (1999a) explored the distinction between disposition and mood with a four-year longitudinal study. Affective disposition was measured twice at one-year intervals, while measures of positive and negative affect were also measured twice at different one-year milestones. The distinction between the two measures of mood is important: the first instrument measured persistent, or dispositional affect, while the second measured affective state, or how the subjects felt on the particular day of measurement. Two supervisory ratings were also taken; one emphasized performance at the time of measurement, and the other measured performance over the past year. Most of the possible relationships between mood at a given time and performance at the same time were not statistically significant, the only one that was being between performance and *negative mood*. However, the measures of *disposition* correlated very well to both performance at the time and performance over the year. Unfortunately, there is no obvious mechanism by which working in a daylit environment could be expected to change a worker’s disposition, although a daylight environment might be less likely to produce a negative mood state.

Organ (1988) introduces another variable into this complex mix by raising the question of what constitutes job performance. He introduces the concept of organizational citizenship behavior (OCB) by which is meant behavior that promotes the objectives of the organization rather than the individual, behavior that can be encapsulated in the term "team player". He makes two arguments why OCB might be important. The first is that OCB may capture variance in the effects of job satisfaction and psychological well-being better than direct measures of performance such as output, because there is less risk for an employee in failing to show cooperation, professional growth, or altruistic behaviors than in actually failing to perform up to job criteria. The second is his speculation that some forms of OCB could be more directly linked to short-term mood; a positive mood on a particular day might lead an employee to help a co-worker in a direct, personal way.

3.8.2 The role of the lighting

Synopsis: Lighting conditions, along with ventilation and privacy conditions, are major factors in determining satisfaction with the physical environment at work. Satisfaction with the physical environment has a modest impact on job satisfaction (which is not discriminated from well-being in this literature) but the link between job satisfaction and work performance is far from clear.

Although doubt still surrounds the exact nature of the link between psychological well-being and job performance, there can be little doubt that there is such a link, so the next question to be considered is what contribution do the physical and environmental characteristics of the workplace make to feelings of well-being? No matter how well-being is conceptualized, whether as disposition or mood, most studies indicate that social and personal factors make the greatest contributions to it (Organ, 1988; Wright and Cropanzano, 1997, 2000). The physical and environmental characteristics of the workplace are assumed to have relatively little influence on the construct, yet they are included in most surveys, and have been shown to play a role when directly studied (Wells, 2000; Hygge and Knez, 2001; Donald and Siu, 2001).

Donald and Siu (2001) looked at perceived environmental conditions and their relationship to employees' ratings of job satisfaction. (As a rule, the literature on environmental psychology does not differentiate between job satisfaction and psychological well-being.) Environmental conditions were more likely to be correlated with job satisfaction among blue-collar workers than among white-collar workers, probably because blue-collar work takes place in dustier, noisier, and more physically stressful conditions.

Sutton and Rafaeli (2001) explicitly asked employees about their satisfaction with the lighting in their workstation but found only a small negative correlation (-0.03) with overall job satisfaction. However, Oldham and Rotchford (1983) found that dark, crowded offices were moderately correlated with low job satisfaction, especially satisfaction with co-workers and supervisors. More convincingly, Veitch et al. (2002) carried out a survey of 419 employees in three different government offices in Canada. Using structural equation modeling, (Beckstead and Boyce, 1992) they showed that satisfaction with lighting, along with satisfaction with ventilation and satisfaction with privacy, influenced satisfaction with the environment and that that, in turn, was loosely linked to job satisfaction. The aspects of lighting contributing to satisfaction with lighting were the amount of lighting on the desk, the amount of light for computer work, the amount of reflected light in the computer screen, the overall quality of the lighting in the work area, and access to a view of the outside.

There can be little doubt that lighting, both electric lighting and daylighting, has a role to play in people's satisfaction with the environment at work and that satisfaction with the environment is linked to job satisfaction. The problem in using this argument to address the effect of daylighting on productivity is that the linkage between environmental satisfaction and job satisfaction is weak and that between job satisfaction and performance is far from clear. Partly this is due to the vagueness in the definition of job satisfaction used by different participants in this field and hence the uncertainty about whether the effects found are due to the cognitive sense of job satisfaction or the emotional response of psychological well-being, and if it is the latter, if this is related to disposition or mood. Clearly, more and better-defined research is needed. Further, there is a need for study of the effects of lighting, including daylighting, on a wider range of outcomes of interest to organizations, such as the ability to recruit and retain workers, the prevalence of asocial behavior, and the performance of cognitive and judgmental tasks.

3.9 Field surveys

Synopsis: Field surveys in a large number of offices, using the same evaluation methodology, have identified two important factors for high levels of satisfaction with the environment and for a high level of self-rated productivity. They are the level of individual control and the depth of the building. Individual control is valued most when the ambient conditions are uncomfortable. This implies that windows should always be fitted with some means of control. Shallow buildings which allow daylighting and natural ventilation to be used are preferred over deep buildings which require electric lighting and mechanical ventilation at all times.

Much of the understanding of the effects of daylight on productivity discussed above has been gained from laboratory studies, where conditions can be closely controlled. An alternative approach is that of field studies, i.e., studies in real buildings. Field studies have the advantage of face validity but suffer from a lack of experimental control that makes interpretation of the results difficult. Further, many field studies are one-offs, in which a unique building is evaluated, using a unique method. It is only by accumulating the results of many such evaluations made using the same method that any general understanding can be developed. Leaman and Bordass (2000) describe just such an extensive set of evaluations made in the UK. Leaman and Bordass (2000) set out to answer the question, "What features of workplaces under the control of designers and managers significantly influence human productivity?" Their research has identified six "killer" variables, i.e., variables that have a critical influence on productivity. These "killer" variables are arranged into four clusters, each cluster containing variables that are more closely related to each other than to the variables in the other clusters. The clusters are labeled "personal control", "responsiveness to complaints", "building depth", and "workgroup". The "responsiveness to complaints" and "workgroup" clusters are matters for management. The degree of "personal control" and "building depth" are matters for the designer.

For personal control, Leaman and Bordass (2000) report that there was a small but statistically significant correlation (r = 0.16 to 0.49) between level of individual control of the environment and self-reported productivity in seven of eleven office buildings evaluated in 1996-97. However, they also make the point that of the five different aspects of the physical environment examined; heating, cooling, lighting, ventilation, and noise, lighting control is the only one that is not statistically significantly linked to self-rated productivity. Further, they report that the correlation between the level of individual control and self-rated productivity tends to decrease as the level of comfort in the building increases. This suggests that personal control is most valued when there is something to do with it, i.e., when the environmental conditions provided are uncomfortable for the individual and the personal control enables the individual to adjust the conditions until comfort is achieved. This suggestion carries two implications. The first is that the reason why individual control of lighting is not significantly linked to self-rated productivity is because the lighting in the offices examined was more satisfactory than were the other physical variables examined. The second is that all windows should have some means of controlling the admission of daylight and sunlight to ensure comfort.

However, a word of warning about the value of personal control is necessary. A study of occupant's reactions to having individual control of lighting in a number of multi-occupied offices has revealed a potential for conflict between occupants, so much so that some occupants avoid using the controls (Moore et al., 2002). When this occurs, the submissive occupants tend to be more negative about the luminous environment and presumably experience a higher level of stress. As in so many aspects of the physical environment, people's reactions to personal control depend on how it is provided and whether it can be used to alleviate their discomfort, without causing other problems for them.

As for building depth, Leaman and Bordass (2000) report that as buildings get deeper, the levels of satisfaction with the building and self-reported productivity decrease. The critical threshold depth appears to be about 15 m, from wall to wall. There are several possible reasons for this finding. Deeper buildings tend to be more complex, and require the use of air conditioning and electric lighting at all times. Shallow buildings may be able to take advantage of natural ventilation, in a suitable climate, and can certainly use daylight when available. What the relative importance of each of these factors is remains to be determined, but the result shown in Figure 8 certainly suggests that the availability of daylight and a view out are appreciated.

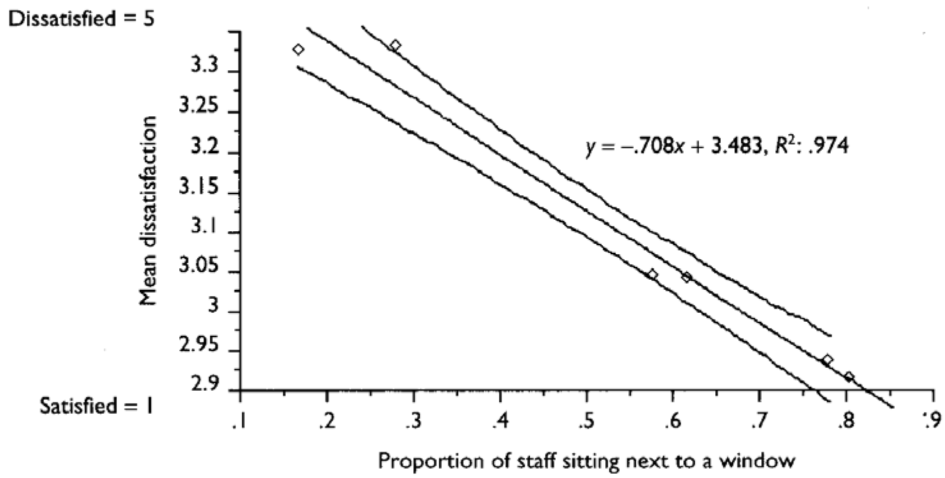

Figure 8: Mean ratings of satisfaction with the physical environment for the occupants of six London office buildings, plotted against the proportion of staff sitting next to a window (Leaman and Bordass, 2000).

4. Daylight and health

Health is important to people and a prerequisite for productivity. The World Health Organization defines health as a state of complete physical, mental, and social well being and not merely the absence of disease and infirmity. Such an utopian ideal is no doubt desirable but it is rather vague as to what might constitute a state of complete social well being. Therefore, this review will concentrate on the proven impacts of light exposure on people's physical and mental states. By proven is meant the impacts where there is a plausible mechanism through which light can have its impact and/or, where light exposure has been used as a treatment for a condition, clinical trials have demonstrated the effectiveness of that treatment. Aspects of light and health that are matters of faith, such as color therapy, are not considered. Neither are aspects of health associated with exposure to light at night (Stevens et al., 1997; Brainard et al., 1999; Graham et al., 2001; Schernhammer and Schulmeister, 2002).

4.1 Light as radiation

People who are exposed to daylight are bathed in electromagnetic radiation in the ultra-violet, visible, and infra-red wavelength ranges. This radiation can have an effect on human health simply as radiation, regardless of whether or not it stimulates the visual system or the circadian system.

4.1.1 Tissue damage

Synopsis: Ultra-violet, visible and infra-red radiation can all cause tissue damage to the eye or skin given a high enough radiant dose. This tissue damage can become evident within a few hours or only after many years.

Exposure to ultra-violet radiation affects both eye and skin. For the eye, exposure to ultra-violet radiation can produce photokeratitis of the cornea. This is a very unpleasant but temporary condition that can result in severe pain beginning several hours after exposure and persisting for twenty-four hours or longer (Pitts and Tredici, 1971). The symptoms of photokeratitis are clouding of the cornea, reddening of the eye, tearing, photophobia, twitching of the eyelids, and a feeling of grit in the eye. The factors that determine whether a person exposed to ultra-violet radiation will experience photokeratitis are the dose; i.e., the product of the irradiance on the eye and the time duration of the exposure, and the actual spectrum of the exposure.

Photokeratitis occurs because of a photochemical reaction to ultra-violet radiation at the cornea of the eye, but not all the ultra-violet radiation incident on the eye is absorbed at the cornea. Significant amounts of longer wavelength ultra-violet radiation reach and are absorbed in the lens. The effect of exposing the lens to ultra-violet radiation is to produce a cataract, an opacity in the lens that absorbs and scatters light, thereby severely degrading the retinal image and diminishing visual capabilities. This cataract formation can occur on two time scales; acute, i.e., with a few hours of exposure, and chronic, i.e., after many years of exposure.

Exposure to ultra-violet radiation also has an effect on the skin. Within a few hours of exposure, the skin reddens. This reddening is called erythema. Erythema reaches a maximum about eight to twelve hours after exposure and fades away after a few days. High-dose exposures may result in edema, pain, blistering, and, after a few days, peeling of the skin, i.e., sunburn. Repeated exposure to ultra-violet radiation produces a protective response in the skin. Specifically, with repeated exposure, pigment migration to the surface of the skin occurs and a new darker pigment is formed. Coincident with this, the outer layer of the skin thickens producing a tan. The effect of these changes is to decrease the sensitivity of the skin to ultra-violet radiation in the wavelength range below 290 nm (Farr and Diffey, 1985).

Electromagnetic radiation in the wavelength range 400 - 1400 nm, i.e. the visible and near infra-red, can damage the retina because radiation in this wavelength range, unlike ultra-violet radiation, is transmitted through the ocular media and so reaches the retina. On arriving at the retina, some photons are absorbed in the photoreceptors, where they initiate the process of vision, while others are absorbed in the pigment epithelium, thereby increasing its temperature. Given enough energy, the temperature of the pigment epithelium can be elevated sufficiently to damage the tissue. This effect goes under the name of chorio-retinal injury. Such injuries have a long history, mostly derived from looking directly at the sun for a prolonged period. The main symptom of chorio-retinal injury is the presence of a "blind spot" or scotoma in the area where the absorption occurred. The location of the injury is important. If it occurs in the fovea, then it severely interferes with vision. If it is small and occurs in the far periphery, it may pass unnoticed. The scotoma can usually be seen under ophthalmic examination within five minutes of exposure and certainly within 24 hours. Recovery from chorio-retinal injury is limited or non-existent. The probability of chorio-retinal injury by exposure to visible and near infra-red radiation basically depends on the retinal radiant exposure, weighted by the appropriate action spectrum, the size of the retinal image, and the possibility of an aversive response before damage occurs.

Chorio-retinal damage is a thermal effect. Photochemical damage of the retina can also occur following exposure to visible wavelengths. This is called photoretinitis. The exact nature of the chemical process by which photoretinitis occurs is not understood but what is known is that it can occur at radiant energy levels less than those required to cause threshold thermal damage. Photoretinitis is rare in practice because the normal aversion to very bright lights causes people to shield their eyes or to look away before damage can occur. However, if exposure is sufficient to cause photoretinitis, the damage will not usually become apparent until about twelve hours later. Some recovery from the damage is possible.

Between 1,400 nm and 1,900 nm, virtually all incident radiation is absorbed in the cornea and aqueous humor of the eye. Above 1,900 nm, the cornea is the sole absorber. The effect of energy in the infra-red region below 1,400 nm that reaches the retina has already been considered in the discussion of chorio-retinal damage. However, infra-red energy that is absorbed either in the ocular media or in the cornea and lens also needs to be considered because it raises the temperature of the tissue where it is absorbed and may, by conduction, raise the temperature of adjacent areas. Fortunately, extremely high corneal irradiances are necessary for changes in the lens to occur within the time taken for the common aversive reaction to occur (200 ms). It is generally considered that the aversive reaction provides protection for the eye against thermal effects of infra-red radiation up to levels in excess of those that cause a flashburn of the skin.

So far, only the acute effect of infra-red radiation has been considered, but there are definitely adverse effects following prolonged exposure to infra-red radiation. Lydahl and Philipson (1984 a and b) have shown an increased incidence of cataract amongst workers who have been exposed to molten glass or metal for many years. Whenever exposure to a light source produces a marked sensation of warmth on the skin, the possibility of long-term infra-red radiation damage to the eye should be considered.

As for the skin, the effect of visible and infra-red radiation is simply to raise the temperature. If the temperature elevation is sufficient, then burns will be produced. It is important to realize that the focusing process of the eye makes it much more sensitive than the skin to such injury for visible radiation and infra-red radiation below 1,400 nm. However, the skin and eye are equally at risk from longer wavelength infra-red radiation because the ocular media are virtually opaque for these wavelengths and the mechanism for acute damage is thermal. The efficiency with which a given irradiance raises the temperature of the skin depends on the exposed area, the reflectance of the skin, and the duration of exposure. The threshold irradiance for thermal injury of the skin is greater than 1 W/cm^2. Such irradiances are very unlikely to be produced by sunlight or by the conventional lighting of interiors.

4.1.2 Threshold limit values

Synopsis: There exist widely recognized criteria by which the magnitude of the hazard posed by different amounts of radiation with different spectral contents can be evaluated. These criteria are called threshold limit values. They represent the levels of exposure to which healthy workers can be repeatedly exposed without adverse health effects.

Given the potential for tissue damage by ultra-violet, visible, and infra-red radiation, it should not be too surprising that there are recommended limits for exposure to such radiation. The American Conference of Governmental Industrial

Hygienists (ACGIH) has published threshold limit values for exposure to ultra-violet radiation, to avoid photokertitis; for exposure to visible radiation, to avoid photoretinitis; and for visible and infra-red radiation, to avoid cataract after prolonged exposure and chorio-retinal injury from low-luminance infra-red illumination sources. The threshold limit values take various forms depending on the size of the source of radiation and the exposure time. For some situations, the threshold limit values are based on total irradiance at the eye, while for others they are based on the spectral irradiance at the eye or the spectral radiance of the source, multiplied by a weighting function based on the action spectrum of the damage being controlled (ACGIH, 2001). These threshold limit values are the levels of exposure and conditions under which it is believed nearly all healthy workers may be repeatedly exposed, day after day, without adverse health effects (Sliney and Bitran, 1998). The recommendations of the ACGIH have been adopted, with slight modifications, by the International Committee on Non-Ionising Radiation Protection (ICNIRP) (Hietanen, 1998). Following any of these recommendations will limit the likelihood of tissue damage by ultra-violet, visible and infra-red radiation. Full details of the threshold limit values can be obtained from the publications of the organizations mentioned (INIRC/IRPA, 1991; ICNIRP, 1991; ICNIRP, 1997, ACGIH, 2001).

4.1.3 Hazardous light sources

Synopsis: Based on the threshold limit values, a system for evaluating commonly used light sources has been developed. Of all the light sources that most people are exposed to, it is sunlight that poses the highest risk of tissue damage. This risk is dramatically reduced when the ultra-violet component of sunlight is reduced by passage through glass.

The Illuminating Engineering Society of North America Recommended Practice 27 (IESNA, 1996) not only adopts the ACGIH criteria for limiting tissue damage, it also gives details of how to make the necessary measurements and sets out a system for classifying light sources according to the level of potential risk they represent. Kohmoto (1999) produced an evaluation of the hazard posed by a range of electric light sources used for general lighting, based on the IESNA (1996) procedure. Both the linear and compact forms of the fluorescent lamps widely used in commercial buildings do not pose a risk of tissue damage. Other electric light sources commonly used for lighting industrial and commercial buildings, such as high-wattage high-pressure sodium, metal halide, and mercury discharge lamps, all pose some risk in some situations. Of all the light sources available, the one to which most people are exposed and which represents the greatest potential for tissue damage is the sun. There is a strong correlation between exposure of the skin to the sun and the development of skin cancer (Moan and Dahlback, 1993). This is because, when overhead, the sun emits copious amounts of ultra-violet, visible, and infra-red radiation. It is the realization of the hazard represented by exposure to optical radiation from the sun that has driven the development of more effective sunscreens to be applied to the skin (Forestier, 1998) and sunglasses to shield the eyes (Sliney, 1995; Mellerio, 1998). However, it is important to appreciate that wearing a sunscreen does not eliminate all the hazards of exposure to sunlight. Sunscreens are effective against the shorter wavelength ultra-violet (UV-B) radiation that is mainly responsible for erythema, but do allow longer wavelength ultra-violet (UV-A) radiation to reach the skin. While these wavelengths are much less effective in producing erythema, they are effective in inducing melanomas, especially on untanned skin (Setlow and Woodhead, 1994). Of course, it is important to appreciate that, for most people, the hazard posed by sunlight is virtually eliminated indoors because transmission through conventional glass eliminates the short wavelength (UV-B) ultra-violet radiation and reduces the longer wavelength (UV-A) radiation.

4.1.4 Special groups

Synopsis: There are some groups of people who are particularly sensitive to ultra-violet radiation. These include newborns, aphakics, and those with enhanced sensitivity due to disease, medication, and exposure to chemical agents. Such people may be sufficiently sensitive that they can suffer tissue damage when sitting near a window.

All the methods for evaluating light sources for tissue damage are based on action spectra linked to the average adult human response to ultra-violet, visible and infra-red radiation. Unfortunately, there are some groups who deviate markedly from that average sensitivity in the direction of making them much more sensitive to radiation in these wavelength ranges.

One such group consists of very premature babies, particularly those weighing less than 1,000 gm at birth. These infants have eyes that are still developing and exposure to light is believed to be involved in the retinopathy of prematurity, a visual disorder that can permanently damage the retina of such babies. Proposals to limit the light exposure of babies in neonatal intensive care units have been made (Bullough and Rea, 1996). Even babies born after a normal gestation period have to be treated with care as regards light exposure because such infants have lenses with significant transmittance in the wavelength range from 300 to 350 nm, i.e., in the UV-B and UV-A regions (Barker and Brainard, 1991). This means care should be taken to limit the exposure of the eyes of newborns to light sources that emit a lot of ultra-violet radiation, such as the sun.

Another population with a problem with exposure to light, but at the opposite end of life, are postoperative cataract patients who have had their lens removed. Such patients are more likely to suffer photochemical retinal damage due to short wavelength visible and ultra-violet radiation exposure than are people with their biological lens intact, unless they are fitted with an ultra-violet-absorbing, intraocular lens as is usually the case today (Werner and Hardenbergh, 1983; Werner et al., 1990, CIE, 1997).

Three other groups who need to take special care about exposure to ultra-violet radiation are those who have medical conditions that enhance photosensitivity, e.g., lupus erythematosus (Rihner and McGrath, 1992); those who are taking pharmaceuticals that increase photosensitivity; and those who are exposed to certain chemical agents in the environment, such as the whiteners used in some household products (Harber et al., 1985). Unlike newborns and aphakics, where the hazard is confined to the retina, the effect of photosensitization primarily increases the hazard to the skin. How much the risk posed by exposure to ultra-violet radiation is increased will depend on the medical condition, or the specific pharmaceutical or chemical and the dose taken and level of exposure, but it may be sufficient that sitting near a window is to be avoided.

4.1.5 Phototherapy

Synopsis: Ultra-violet irradiation of the skin is important for the production of vitamin D. Vitamin D deficiency is linked to rickets, osteomalacia, and various forms of cancer. Exposure to sunlight outdoors is the simplest way to get a dose of ultra-violet radiation. Ultra-violet radiation is also used in the medical treatment of such conditions as hyperbilirubinemia, psoriasis, eczema, and some tumors.

The effects of light as radiation on health considered so far have all been negative, but there are some positive effects. For example, exposure to ultra-violet radiation is important for the production of Vitamin D in the skin. Vitamin D deficiency has widespread effects on human health. Most obvious are the bone softening diseases such as rickets in children and osteomalacia in adults, but it also has an important function in regulating cell growth and differentiation (Holick, 2002). Vitamin D deficiency has been associated with an increased risk of death due to colon, breast, prostate and ovarian cancer, as well as developing diabetes and multiple sclerosis (Garland et al., 1989; Malabanan et al., 1998; Ahonen et al., 2000; Hypponen et al., 2001). Most of the vitamin D requirements of children and adults can be met by exposure to sunlight outdoors, but current lifestyles, which involve long periods indoors and the wearing of sunscreens when outdoors in sunlight have increased the risk of vitamin D deficiency (Tangpricha et al., 2002). Groups who cannot achieve sufficient exposure, such as the infirm, or those who live in areas where sunlight is limited for several months, or those who have limited exposure and very dark skin, must depend on dietary sources and vitamin supplements to meet their vitamin D requirement, although what constitutes an appropriate dose in the absence of exposure to sunlight is currently the subject of discussion (Glerup et al., 2000).

There are also a number of other medical conditions where exposure to light as radiation has been shown to be helpful (Parrish et al., 1985). Hyperbilirubinemia, commonly known as jaundice of the newborn, occurs frequently enough so that about 7 to 10 percent of babies born in the US require medical attention. Severe cases can lead to brain damage and death. The phototherapy for this condition involves exposing the naked baby to short-wavelength visible radiation, with the eyes shielded (Agati, 2002). Ultra-violet radiation is also used in the treatment of skin diseases such as psoriasis and eczema. Patients are given multiple whole-body exposures to sub-erythemogenic doses of ultra-violet radiation. An alternative treatment for severe psoriasis, eczema, vitiligo and some other skin disorders uses a combination of exposure to ultra-violet radiation and a psolaren. This combined treatment is known as photochemotherapy. Chemotherapy operates by killing cells. The general problem of chemotherapy is how to limit this destruction to the desired cells. Psolaren has the potential to kill cells but it requires exposure to ultra-violet radiation to trigger the effect. Fortunately, ultra-violet radiation penetrates the skin but does not reach internal organs, so the combination of psolaren and ultra-violet radiation limits the cytotoxic effects to the skin. This should not be taken to mean that photochemotherapy is without risk. Basal and squamous cell skin cancers have been found on patients who have been treated by photochemotherapy. As in so many medical problems, the decision whether to use photochemotherapy or not is a matter of balancing one risk against another. Photochemotherapy can also be used to treat internal tumors. A chemical, which when injected into the blood stream binds to tumor cells, is triggered to kill the tumor cells by exposure to visible radiation of 630 nm delivered via an endoscope. This process, which is also known as photodynamic therapy, has been shown to be effective against a wide range of tumors (Epstein, 1989). One other use of ultra-violet radiation is in the suppression of the immune system (Noonan and De Fabo, 1994). Such suppression may be helpful in cases of autoimmune diseases such as multiple sclerosis, where hyperactivity of the immune system is a problem. Of course, it may also be dangerous for people who are already immuno-suppressed. Therapeutic exposure to light is usually only undertaken after consulting a qualified physician.

4.1.6 Aging effects

Synopsis: Some argue that the probability of retinal damage is related to the amount of light received at the eye over life, but this is unproven. What is proven is that prolonged exposure to the sun results in skin aging.

In addition to the hazards and benefits of exposure to ultra-violet, visible, and infra-red radiation discussed above, there are possible effects of such exposure on the rate at which aging progresses. One example is the possibility of a link between the total light exposure over life and the likelihood of retinal damage. The proposed mechanism is that exposure to light causes damage to the retina. This damage can be repaired, but the repair mechanisms become less effective with age, resulting in damage that accumulates more rapidly with greater retinal exposure to light (Marshall, 1981; Young, 1981). There is no doubt that the probability of retinal deterioration increases with age, and there are close similarities between the changes induced in the retina as a result of the aging process and those elicited by exposure to high levels of illumination (World Health Organization, 1982), but whether it is really exposure to light that is responsible for the aging process in the retina is open to question. What is needed are comprehensive epidemiological studies examining the link between light exposure history and retinal deterioration with age. Until they are done, the effect of prolonged exposure to high levels of light on the rate of aging of the retina must remain unproven. Nonetheless, the possibility of such an aging effect suggests it would be wise to protect the eyes in the presence of bright sunlight.

The other aging effect of prolonged exposure to radiation is well established and affects the skin. The most striking feature of severely photoaged skin is the presence of massive quantities of thickened, degraded elastic fibers which degenerate into amorphous masses. The result is a thicker skin resembling a crust. Photoaging is most commonly seen on the parts of the body that are not usually protected by clothing. The action spectrum for photoaging is not well defined, but it is clear that the dominant radiation is in the ultra-violet (Cesarini, 1998). Wearing a sunscreen while outdoors, particularly in regions where sunlight is copious, and filtering sunlight through glass will provide some protection against the photoaging process.

4.2 Health effects of light operating through the visual system

4.2.1 Eyestrain

Synopsis: The symptoms of eyestrain, such as sore eyes, blurred vision, and headaches, can be produced by both electric lighting and daylighting.

Light is a necessity for the visual system to operate, but if used in the wrong way, it can be injurious to health. The most common effect of lighting operating through the visual system on health is colloquially known as eyestrain. The symptoms of eyestrain are irritation of the eyes, evident as inflammation of the eyes and lids; breakdown of vision, evident as blurring or double vision; and referred effects, usually in the form of headaches, indigestion etc. Eyestrain is usually temporary but anyone who regularly experiences one or more of the symptoms of eyestrain cannot be said to be enjoying the best of health.

These symptoms can be brought about by poor lighting, the inherent features of the task and its surroundings, inadequacies in the individual's visual system, or some combination of these factors. There are two routes by which eyestrain can be caused, one physiological and one perceptual. The physiological route is through muscular strain occurring in the ocularmotor system, i.e., in the muscle systems that control the fixation, accommodation, convergence, and pupil size of the eyes. The perceptual route is evident as the stress that is felt when the visual system has difficulty in achieving its primary aim, to make sense of the world around us. Conditions that require the ocularmotor system to hold a fixed position for a long time or to make frequent changes of the same type are likely to produce eyestrain through muscular exhaustion. Conditions that make it difficult to see what needs to be seen or which distract attention from what needs to be seen are likely to produce eyestrain through stress. Lighting conditions which have been shown to lead to eyestrain are inadequate illuminance for the task (Simonson and Brozek, 1948), excessive luminance ratios between different elements of a task (Wibom and Carlsson, 1987), and lamp flicker, even when it is not visible (Wilkins et al., 1989). Daylighting will usually provide more than adequate illuminance on the task and is certainly free of flicker, but is prone to produce excessive luminance ratios, as the luminance of the sky is usually much higher than the luminances of interior walls forming the surround of a window. Regularly occurring eyestrain is inimical to productivity, not only for its effect on visual capabilities, but also because of the way it may alter people's behavior. Heerwagen et al. (1992) found that office workers used a variety of tactics to reduce discomfort. Among them were walking around, going to get a drink, complaining to colleagues, and introducing ad-hoc modifications to the environment. Some of these activities are likely to detract from productivity.

4.2.2 Migraine

Synopsis: People who suffer from migraine are sensitive to visual instability, produced temporally by lamp flicker, or spatially by large-area, high-contrast patterns. Daylighting will reduce the modulation of lamp flicker but increase the visibility of strong patterns.

Everyone is likely to experience eyestrain in poor lighting condition, but there are some groups who are particularly sensitive to lighting conditions. One such group are those who suffer from photoepilepsy. Given fluctuating light of the right frequency, covering a large area, and at a high percentage modulation, these individuals can be driven into a seizure. The frequency to which people with photoepilepsy are most sensitive is about 15 Hz, although about 50 percent still show signs of a photoconvulsive response at 50 Hz (Jeavons and Harding, 1975). Seizures start in the visual cortex and occur when normal physiological excitation involves more than a critical cortical area and are most likely when that cortical excitation is rhythmic (Wilkins, 1995). Daylighting, *per se*, should not trigger a seizure unless sunlight arrives in a space after passing through a moving filter, such as a tree outside a window that is moving in the wind.

A larger but related group who can suffer adverse consequences of exposure to light are migraineurs. Migraine has been described as a neurovascular reaction to changes in the individual's internal or external environment. A migraine attack is much more than a severe headache. Nausea, vomiting, intolerance of smells, and photophobia can all be part of a migraine attack. The exact cause of a migraine is not known, but Wilkins (1995) speculates that cortical hyperexcitability linked to the magnocellular pathway of the visual system is responsible for triggering a migraine attack. What is known is that migraineurs are more sensitive to light than people who do not experience migraine, even when they are headache-free (Main et al., 1997). This means migraineurs are much more likely to experience glare and to complain about high light levels. This makes them particularly susceptible to daylight and sunlight through windows.

Migraineurs are likely to be hypersensitive to visual instability, no matter whether it is produced by fluctuations in light output from a light source over time, or by large-area, high-contrast, repetitive patterns over a space (Marcus and Soso, 1989; Wilkins, 1995). Daylight is a mixed blessing for migraineurs. Given its stability, it is obvious that the presence of daylight will tend to reduce the percentage modulation of any light fluctuations produced by the electric lighting operating from the alternating current supply. However, high illuminances such as are produced by daylighting will also tend to exacerbate the disturbing effects of any large-area, repetitive, high-contrast patterns.

4.2.3 Autism

Synopsis: Autistics have a chronically high level of arousal. The repetitive behavior they typically exhibit is believed to be a means of dealing with this problem. The amount and variability of light provided by daylighting may make life difficult for autistics.

Another group who can be expected to be sensitive to variations in light output are the autistic. Autism is a neurological disorder that affects a child's ability to communicate, understand language, play, and relate to others. Symptoms are repetitive activities, stereotyped movements, resistance to changes in the environment and the daily routine, and unusual responses to sensory experiences. The level of arousal of autistic children is chronically high, and repetitive behaviors are believed to be a way of regulating it (Hutt et al., 1964). This implies that an increase in environmental stimulation will generate an increase in repetitive behavior. The high light levels often provided by daylight are inherently arousing. Further, the variation in lighting of an interior that is associated with daylighting, especially when there are scattered clouds in the sky, can be regarded as a form of environmental stimulation.

4.3 Health effects of light operating through the circadian system.

4.3.1 Sleep

Synopsis: Advanced sleep phase disorder is a common problem of the elderly, as is sleep onset insomnia and sleep maintenance insomnia. Delayed sleep phase disorder is a problem of the young. Exposure to bright light at an appropriate time can alleviate these problems. Exposure to daylight is a convenient way to provide such bright light exposure.

The sleep / wake cycle is one of the most obvious and important of the circadian rhythms. There are a number of common sleep disorders. Those susceptible to treatment with light are concerned with the timing and duration of sleep. Those associated with timing are delayed and advanced sleep phase disorders. Delayed phase sleep phase disorder is characterized by late sleep onset and late awakening, and is predominantly experienced by young people. Delayed sleep phase disorder need not necessarily cause a problem, provided sleep duration is normal and the individual can adjust his/her work and social schedules to his/her sleep pattern. However, if sleep duration is reduced and/or the timing of sleep is inconsistent with such societal requirements as being at work at a fixed time, then chronic sleep debt is likely. People with chronic sleep debt feel permanently tired and are unlikely to work effectively.

Advanced phase sleep disorder is characterized by early sleep onset and early morning awakening and is predominantly experienced by the elderly. Again, advanced sleep phase disorder may not cause a problem as long as the duration of sleep is normal and the individual's lifestyle can be adjusted to accommodate it.

Exposure to light has been shown to be an effective treatment for these sleep disorders. Czeisler et al. (1988) have demonstrated that exposure to 10,000 lx at appropriate times results in significant phase advances for people with delayed sleep phase disorder and significant phase delay for those with advanced sleep phase disorder. The appropriate times are immediately on awakening for the delayed sleep phase disorder and in the evening for the advanced sleep phase disorder. Campbell et al. (1993), in a study of elderly patients with advanced sleep phase disorder, showed not only a phase delay following exposure to 4000 lx in the evening but also an improvement in sleep quality.

As for sleep duration disorders, the classic problems are sleep onset insomnia with normal awakening and normal sleep onset with sleep maintenance insomnia. Both these disorders are common in the elderly (Foley et al., 1995). Campbell and Dawson (1991) and Lack and Schumacher (1993) have shown that exposure to bright light in the evening produces longer and better quality sleep for people who were experiencing sleep maintenance insomnia.

There can be little doubt that exposure to enough light at the right time is helpful in promoting sleep, but what is enough light, how long should exposure last, and what spectrum should the light have? Unfortunately, there are no clear answers to these questions. A wide range of illuminances, from 2,500 lx to 10,000 lx, a range of times, from 15 minutes to 4 hours, and a wide range of spectra, from fluorescent lamps to sunlight, have been shown to be effective in the treatment of sleep disorders (Terman et al., 1995). What is clear is that daylight, assuming it is available at the required time, is a convenient means to provide the high light levels apparently required to sustain the operation of the circadian system.

4.3.2 Seasonal affective disorder

Synopsis: Seasonal affective disorder is a seasonal form of depression. Exposure to bright light has been shown to alleviate this depression. Daylight is a convenient means to provide such exposure.

Depression is one of the most common psychiatric conditions in patients visiting a doctor, with a lifetime prevalence of about 17 percent (Kessler et al., 1994). Seasonal Affective Disorder (SAD) is a subtype of major depression that is identified by a regular relationship between the onset of depression and the time of year; full remission of depression at another time of year; the pattern of onset and remission of depression at specific times of the year repeated over the last two years; no non-seasonal depression over the last two years; and episodes of seasonal depression substantially outnumbering non-seasonal depression over the individual's lifetime (American Psychiatric Association, 2000). Two forms of SAD have been identified, winter and summer SAD, the former being much more common than the latter. Winter SAD can be recognized by the increase in feelings of depression and a reduced interest in all or most activities, typical of depression, together with such atypical symptoms as increased sleep, increased irritability, and increased appetite with carbohydrate cravings and consequent weight gain. These symptoms disappear in Summer. Summer SAD is also associated with an increase in feelings of depression and lack of interest in activities, but in this case there is a decrease in sleep, poor appetite and weight loss (Wehr et al., 1991). Winter SAD is experienced by about 5 percent of the population, and about 10 to 20 percent have sub-syndromal symptoms, the percentages tending to increase with an increase in latitude (Kasper et al., 1989; Wehr and Rosenthal, 1989). Winter SAD is more common in females than males (Rosen et al., 1990). Its prevalence increases with age until about the sixth decade.

The cause of winter SAD is unknown. Explanations based on disturbances to the circadian system, melatonin concentration, and regulation of the hormone serotonin have been proposed but none have been proven. While the cause of winter SAD is unclear, what is clear is that exposure to bright light is often an effective treatment (Rosenthal et al., 1985; Terman et al., 1989; Tam et al., 1995), although whether this is because of some physiological effect or a placebo effect is open to question (Eastman, 1990; Eastman et al., 1992). What is meant by "bright light" is usually exposure to a light box that produces an illuminance at the eye of between 2,500 lx and 10,000 lx. Exposure durations range from 2 hours for 2,500 lx to 30 minutes for 10,000 lx. The timing of the exposure to "bright light" is relatively unimportant (Wirz-Justice et al., 1993). Light boxes usually contain fluorescent lamps as a light source, but there is no doubt that daylight could also be used as a source of "bright light."

Response to "bright light" can usually be expected with two to four days and a measurable improvement is often seen within one week, but symptoms will reappear if light treatment is discontinued. The symptoms that are atypical of depression in general are the ones that are most responsive to light treatment, i.e., hypersomnia, increased appetite, and carbohydrate cravings. As with most medical treatments, there are side effects of prolonged exposure to the high illuminances of a light box. Typically they are mild disturbances of vision and headaches that subside with time. However, care should be taken with patients who have a tendency towards mania, and whose skin is photosensitive, or who already have retinal damage, or who have a medical condition that makes retinal damage likely (Levitt et al., 1993; Gallin et al., 1995; Kogan and Guilford, 1998). General guidance on the use of light in the treatment of SAD is available from a number of sources (Saeed and Bruce, 1998; Lam, 1998; Lam and Levitt, 1999).

4.3.3 Alzheimer's disease

Synopsis: Alzheimers disease is the most common form of dementia. People with Alzheimer's disease have reduced visual capabilities and fractured circadian rhythms. Daylighting provided without glare should improve the vision of Alzheimer's patients. Exposure to bright light during the day has been shown to improve the regularity of their circadian rhythm, which will reduce the prevalence of such undesirable behavior as nighttime wandering.

Alzheimer's disease is a degenerative disease of the brain and is the most common cause of dementia. It first becomes evident to the external observer when the individual starts forgetting recent events or familiar tasks. As it develops, memory loss becomes more global, accompanied by personality change and reduced communication. Lighting can influence the abilities and behavior of people with Alzheimer's disease, operating through both the visual system and the circadian system. Alzheimer's patients show a reduced contrast sensitivity function relative to healthy people of the same age (Gilmore and Whitehouse, 1995) that is consistent with the reports of cell loss at both retinal and cortical level in Alzheimer's disease (Blanks et al, 1989; Hof and Morrison, 1990; Kurylo et al., 1991). It has been argued that such reduced visual capabilities may exacerbate the effects of other cognitive losses in Alzheimer's patients, tending to increase confusion and social isolation (Mendez et al., 1990; Uhlman et al., 1991). This suggests that enhancing the luminance contrast of the stimulus would improve the functioning of Alzheimer's patients. Gilmore et al. (1996) have shown that increasing the luminance contrast does increase the speed of letter recognition by Alzheimer's patients. This finding, suggesting as it does that Alzheimer's patients are struggling to make sense of the world with diminished visual and cognitive capabilities, raises the intriguing possibility that daylighting, with its high light levels and good color rendering properties, would be of advantage for the visual capabilities of Alzheimer's patients, provided it is delivered without glare.

As for the circadian system, people with Alzheimer's disease and other forms of dementia often demonstrate fragmented rest / activity patterns throughout the day and night (Aharon-Peretz et al., 1991; Van Someren et al., 1996). This makes such patients difficult to care for and is one of the main reasons for having them institutionalized (Pollak and Perlick, 1991). The human circadian system is controlled by the suprachiasmatic nucleus, which in turn is entrained by exposure to alternate periods of light and dark. Degeneration is evident in the suprachiasmatic nucleus of people with Alzheimer's disease (Swaab et al., 1985).

Further, people with Alzheimer's disease are not likely to be go outdoors frequently because of the need for constant supervision, which implies they will rarely be exposed to bright light (Campbell et al., 1988). These observations suggest that exposing Alzheimer's patients to bright light during the day and little light at night, thereby increasing the signal strength for entrainment, would help to make their rest activity patterns more stable. Studies using light boxes of the type used for the treatment of seasonal affective disorder have been used to demonstrate such benefits (Okawa et al., 1989; Lovell et al., 1995). Specifically, patients were placed in front of a light box producing 1500 to 3000 lx at the eyes for two hours during the day. The result was reduced agitation and wandering at night and more stable rest / activity rhythms. Unfortunately, Alzheimer's patients are not the most compliant as regards instructions, so continuous supervision is necessary to keep the patient in front of the light box. A more practical alternative is to increase the general illuminance to a high level in rooms where patients spend their days. Van Someren et al. (1997) tested this approach using twenty-two institutionalized patients with various forms of dementia. The average illuminance on the eyes of these patients when in their living rooms was increased from 436 lx to 1136 lx by changing the lighting installation. After four weeks, the installation was returned to its original state, the resulting average illuminance being 372 lx. Figure 9 shows the raw activity data for a patient with Alzheimer's disease and the average twenty-four hour activity level for all patients, for the three lighting conditions. The decreased variability in activity and the generally low level of activity at night under the bright light conditions is obvious. Further, a careful regression analysis of the data showed that patients with severe visual impairment did not benefit from exposure to bright light, suggesting that the bright light is not acting as a placebo. There can be little doubt that lighting has a role to play in the management of Alzheimer's patients and maybe that of patients with other forms of dementia. Further, it may be that daylighting is the most convenient means of providing high light levels for people with Alzheimer's disease.

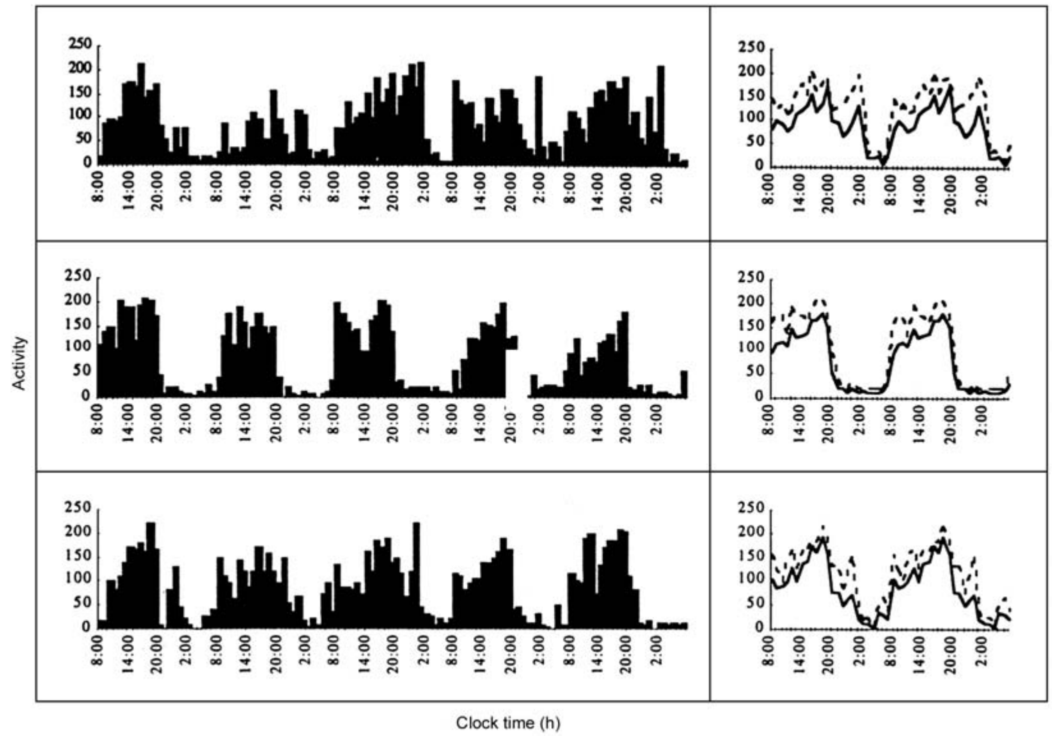

Figure 9: Raw hourly activity data of a patient with Alzheimer's disease over five days, before (upper panel), during (middle panel), and after (lower panel) bright light treatment. The right panels show the average activity levels over 48 hours for 22 subjects with various forms of dementia for the same light exposure conditions (Van Someren et al., 1997).

4.4 Stress

Synopsis: Stress is a common feature of modern life. A view through a window has been suggested as a reliable means of relieving stress.

Stress is a portmanteau term for the physiological and hormonal changes that the body makes in response to threatening or unpleasant events. Events that can give rise to stress are life events such as a divorce; emotional activities such as a full-volume argument with a colleague; and persistent unavoidable, uncomfortable environmental conditions, such as glare, noise, and overcrowding. Prolonged experience of stress can have undesirable health effects, such as headaches, stomach ulcers, and high blood pressure; and changes in behavior that affect productivity, such as absenteeism, high turnover of employees, and poor job performance (Cooper and Payne, 1988). The interesting possibility of relevance to this review is that a view of a natural scene through a window (real or simulated) has been suggested as a means of relieving stress (Clearwater and Coss, 1991; Kaplan, 1992; Ulrich, 1993). If this is so, then given the increased pace of change in much modern business and the consequent increase in stress (Sutherland and Cooper, 2002), having some windows may be a useful countermeasure.

5. Daylighting and finance

Deciding to provide extensive daylighting, limited daylighting, or no daylighting in a building may have financial consequences. These consequences may involve the capital cost of the building, its rental value, and its maintenance costs, all of which influence the return on investment. These costs should also be compared with the alternatives. Some form of lighting is required in all buildings, so if daylighting is not chosen, then the costs of providing electric lighting have to be considered.

This discussion of the financial impacts of daylighting is focussed on the developer and owner as these are the people who often make the decision to use daylighting. However, there is also a societal perspective on daylighting. This perspective says that, over the long term, increasing the use of daylight in buildings will lead to a more sustainable energy economy, something that will be good for the environment and for the nation's economy.

5.1 Capital costs of daylighting

Synopsis: Providing windows is more expensive than providing blank walls. Yet windows are widely used. This observation demonstrates the value placed upon the admission of daylight and a view out.

In comparison to curtain walling, windows are both expensive and poorly insulating. Means Light Commercial Cost Data (Means, 2002) gives typical costs per unit area of $4.25 per square foot installed for concrete block walls, $5.90 per square foot installed for tilt-up concrete wall panels, and $19.55 per square foot for exterior brick face cavity wall, versus $20.70 per square foot installed for the cheapest form of glazed curtain wall. Further, glazing requires more frequent cleaning than exterior walls. The cost for such cleaning is typically $0.08 / square foot (Means, 1997). Of course, there are high-end cladding materials, such as stone, with which glazing is competitive in price but these are the exception rather than the rule. As for insulation, modern walls typically have U values of 0.35 W/m^2K or less; windows typically only achieve 1-2 W/m^2K (as an average, rather than center-pane value) although the additional energy costs implied by this lower U value for glazing may be offset by the reduction in energy costs due to the reduced use of electric lighting. Nonetheless, the continuing widespread use of windows in commercial buildings requires some explanation; why do developers continue to invest in these costly elements? Part of the answer is no doubt the widespread preference for daylight and a view out discussed in Section 3.7. Another is probably the status of windows and atria. There is an evident correlation between the widespread use of daylighting, through either extensive glazing or large atria, and the prestige of the building. An explanation of this can be given in terms of the demagogic function of commercial buildings. For this role the presence of windows or atria may function much like the presence of marble cladding – to impress and intimidate. Another explanation can be found in the use of daylight provision as a reflection of the status of the occupants, the corporate headquarters is much more likely to have extensive glazing or an atrium than is a small branch office.

5.2 Rental value of daylighting

Synopsis: There is anecdotal evidence that the complete absence of windows reduces the rent that can be asked for an office. Unfortunately, there is little evidence about the effect of different levels and types of daylighting on rental value.

The rental value of property can be considered in two forms, as rent per unit area, and as time the property remains empty. Property developers and realtors are trained to be systematic and consistent in their appraisal of the value of commercial space. Fanning et al. (1994) list the physical features to be considered when appraising an office building (See Table 2). The interesting point is that daylighting is not mentioned, although the HVAC system is. Possibly this omission occurs because the vast majority of office buildings have windows, so daylighting does not provide a basis for discriminating between buildings. We were unable to find any property professional who could put a specific figure on the value of good quality daylighting, although several mentioned that a virtual absence of windows would reduce the rental value of a property by between $2 and $4 per square foot. Typical urban office space costs between $15 and $20 per square foot, less in suburban areas and significantly more in the center of major cities. What this implies is that an absence of windows causes approximately a 20 percent reduction in rental value. As for the effect of different numbers and layout of windows; i.e., on the amount and type of daylighting, our literature search yielded no specific research on the effect of daylighting on the capital or rental value of office space. The library of the US Society of Realtors were also unable to find any relevant data.

As for the time a building might stand empty, no information was found about how this varies with the presence or absence of windows. However, Mudarri (2000) provides an example of the return on investment of an improved physical environment. In this calculation, he argues that tenant retention is valuable to a building owner. By retaining a tenant on a new lease, the owner avoids the expenses associated with buildout and brokerage fees, as well as the lost income associated with the four months the building typically stands empty. Further, a survey of tenants has shown that poor indoor air quality and the related issues of thermal comfort and air conditioning performance are most frequently perceived as the worst management operational or design problems for tenants (24 percent); if these problems could be eliminated, the estimated productivity gain would be 18 percent (BOMAI, 1988). Compared to these, the percentage of tenants thinking **Table 2.** Physical features of an office considered in appraising the building (Fanning et al., 1994)

Feature	Explanation
Building design and construction materials	These change with new technology and human preferences. Adaptability of the space for different tenants is important.
Signage	Poor signage reflects on the quality of the building.
Exterior lighting	Exterior lighting of the building and the parking areas promotes public safety.
Street layout	Access to the building is important as is the traffic capacity of adjacent streets
Utilities	The capacity of utilities providing water, electricity, gas and telephone service, and sanitary and storm sewers are important for building adaptability.
Parking	Enough parking is essential in suburban areas. In urban areas, parking may be limited if mass transit is close by.
Lotting and building lines	The proportion of the site covered by the building is important for future expansion.
Landscaping and grading	Landscaping makes the site around the building attractive. Grading is necessary for good drainage.
Office space layout	Matching the office layout to the requirements of potential tenants is important, as is the ability to meet future change.
Tenant finish	Alterations to meet tenant requirements are usually necessary. A building that can be easily altered to meet such needs has a competitive advantage.
Floor sizes	Different tenants require different amounts of space. A building that is flexible enough to accommodate both full-floor and small-space users has a competitive advantage.
Stairways, corridors and elevators	Stairways and corridors often create the first impression of a building. The elevator should be dependable and waiting time should be limited.
Electrical system	The electrical system should have sufficient capacity to meet future demand.
Heating, ventilation and air conditioning	The efficiency, reliability, and effectiveness of the HVAC system is important for occupant satisfaction.
Amenities	The presence of amenities either in the building or nearby is desirable.
Security	Security for personnel and property is important for ease of letting.

that windows were the worst problem was small (2.1 percent) and the estimated productivity gain was also small (4 percent). This finding again suggests that lighting is less likely to cause problems for people than other factors in the physical environment, such as air conditioning (c.f. Section 3.9).

5.3 Daylighting and building accreditation

Synopsis: Interior lighting is not a standard element in the appraisal of buildings. However, there are now a number of accreditation schemes for office buildings. These schemes usually include an element that gives extra points for widespread daylighting. Such schemes have the potential to increase the actual and rental value of property.

Building accreditation programs range from the truly voluntary to some that market forces make almost mandatory. Building accreditation programs have the potential to influence the capital and rental value of a building.

The best-known building accreditation program in the US is The Leadership in Energy and Environmental Design (LEED). This accreditation system was established in 1999 by the US Green Buildings Council, and has recently published a pilot for the LEED-CI Rating System for Commercial [office] Interiors. This accreditation is entirely voluntary, and to acquire it, a building owner must prove that the building meets certain environmental standards for sustainability, efficiency, and indoor environmental quality. Of the 57 available credits, one involves daylighting. Specifically, one credit can be obtained by ensuring a minimum of 2 percent daylight factor over 75 percent of the floorspace, and another by ensuring a direct line of sight to vision glazing from 90 percent of the floorspace.

LEED is similar in spirit, though different in detail, to the Building Research Establishment Environmental Assessment Method (BREEAM) started in the UK in 1990. Although this scheme is also voluntary, around 25 percent of new office buildings in the UK now carry BREEAM accreditation, and the accreditation is widely understood and valued by property agents in the UK.

Some building accreditation programs approach the status of de facto standards. Following the widespread adoption of outsourced property management during the 1990s, there are several fast-growing national and global organizations of property professionals which, to varying degrees, seek to apply standards to office space, to allow more accurate and objective assessments of value to be made. The US-based Building Owners and Managers Association International (BOMAI) promotes a loose system of classification based on a subjective assessment of the prestige of the building, although they stress that BOMAI itself does not classify buildings. A similar organization in the UK, the British Council for Offices has published a guide to “Best Practice in the Specification for Offices” which has become a de facto standard for high-specification office space in the UK. It requires a minimum daylight factor of 0.5%, with an average of 2-5%.

Mandatory national energy efficiency standards often act in favor of daylit spaces, although they penalize excessive areas of glazing. Again drawing on the British model, Part L (2002) of the UK Building Regulations allows an exemption from lighting power density requirements for spaces which are "daylit", i.e., which have a daylight factor of 2 percent over 80 percent of the floor area, and use photoelectric controls. Compliance with Part L is mandatory, so in this sense daylighting does not present a financial 'opportunity'; however, compliance with the daylighting requirements means that designers and owners may reduce performance and therefore costs in other aspects of the building fabric, or alternatively design in features which are inefficient but desirable to tenants, and still achieve overall compliance with Part L.

The proposed 2003 amendments to California's Title 24 requirements, to be implemented in 2005, take a similar approach. Office buildings must use no more than 1.1 W/ft^2 for lighting. This figure is difficult to meet without the use of "adjustment factors" which involve the presence of lighting control systems including motion sensors, manual switches, and photoelectric controls. The adjustment factor allowed for installing photoelectric controls depends on the window area of the façade and the transmittance of the windows, but can be up to 40 percent. This method seems to favor the presence of windows, but it should be noted that Title 24, like Part L, is concerned with the overall energy budget of buildings, and so large areas of glazing must use high-performance glass in order to meet U-factor requirements.

Amendments to building legislation outside the US have been shown to be effective in altering the financial balance in favor of daylighting. The Netherlands is a well-known example of a country in which daylighting is enshrined as an integral part of architecture, through government legislation. The US Federal Government's stated position is that it favors the use of existing or nascent market forces, rather than legislation, to bring about changes in practice, so it seems unlikely that Federal legislation in favor of daylighting will be passed.

5.4 Effect of daylight and view on health costs and outcomes

Synopsis: Health costs are an important consideration for many employers. There is some evidence that people in stressful situations who have access to a natural view make fewer calls on the healthcare provider than those who do not have such a view.

In the US, health coverage for employees is usually organized by the employer. The cost of such coverage may be influenced by the frequency of visits or calls made to healthcare providers, and the employer is also directly affected by the number of sick hours or days taken by employees. Minimizing the health costs of the workforce is a significant financial factor for employers.

Moore (1981) studied the healthcare demands of prisoners, and found that those whose windows looked out over hills and farmland made significantly fewer sick calls to the prison infirmary than those whose windows overlooked the prison yard. View through a window has also been found to influence recovery from surgery. Ulrich (1984) found that patients whose rooms afforded a view of the natural landscape rather than of other buildings spent fewer days in hospital (7.96 compared with 8.70), and that nurses recorded fewer negative comments regarding their progress. Similarly, Keep and Inman (1980) found that patients in a windowless intensive care units showed more confusion. Exactly what aspects of windows are responsible for these effects is unclear. Verderber (1986) conducted an analysis which isolated 21 different reasons why hospital patients and staff preferred windows with a view to either windows without a view, or windowless rooms.

5.5 Daylight and retailing

Synopsis: A number of studies have been undertaken to examine the effect of daylighting on retailing. There is some indication that providing daylight though skylights in deep buildings without any other form of daylight has a small but positive effect on sales. Whether this is due to changes in visibility of merchandise, changes in store appearance, or changes in architecture, is open to question.

Another area where daylighting may have a monetary value beyond that implied by saving energy is in retailing. The question of interest here is whether a daylit space will enhance sales. The benefits of lighting for selling have been the subject of anecdotal reports (Pierson, 1995; Edwards and Torcellini, 2002) but very few containing what could be regarded as evidence. One that does contain evidence of the impact of electric lighting on sales is a study by Cuttle and Brandston (1995) in two furniture galleries. The new electric lighting provided higher illuminances and a more even light distribution on the furniture. Over the five months after the lighting was changed, sales in one gallery increased by 35 percent, but there was no consistent change in sales in the other gallery. Bear in mind that a furniture store is characterized by small numbers of people spending large sums of money, infrequently, to buy goods with which they will live for many years, so the data may be unstable. In another study, Boyce et al. (1996) tracked sales through a process of upgrading the visual environment of several parts of a small supermarket, a business characterized by large numbers of people spending modest sums of money, regularly, to buy goods which will be rapidly consumed. In this case, the refurbishment of the in-store bakery, a refurbishment that involved changes in the layout of the sales area and in the display methods as well as changes in the electric lighting, and the introduction of daylight through skylights, produced statistically significant, sustained increases in the dollar value of sales. Changes in other parts of the store, which were changes in electric lighting alone, did not produce any statistically significant changes in number or dollar value of sales.

Probably the most convincing evidence that daylight can have an influence on sales is a study of sales in a retail chain operating 108 stores, two-thirds with diffusing skylights and one-third without (Heschong-Mahone, 1999a; Heschong et al., 2002a). The design, operation and layout of all the stores was very similar. The only obvious differences between the stores with skylights and those without, apart from the skylights, were the generally higher ceilings and the photosensor control of the fluorescent lighting under the skylights. After dark, the appearance of all the stores was similar. By day, the illuminances under the skylights were often much higher than those provided by the electric lighting in the stores without skylights. Sales were measured by a sales index which quantified the gross sales per store over an 18-month period. The effect of eight different factors on the sales index was examined using stepwise multiple linear regression. The factors found to statistically significantly influence the sales index were the hours for which the store was open per week, the years since the last retrofit of the store, the presence of skylights, local population size, and the average income of that population. Factors that had no statistically significant effect on the sales index were the floor area of the store, probably because the stores were all approximately the same size so there was little variation in this variable, the years since the original opening, and the architectural design. The magnitude of the effect of the factors that were statistically significant is given by the variance in the sales index explained. These values were 16 percent by the hours of opening, 9 percent by the years since the last retrofit, 4 percent by the presence of skylights, 2 percent for the population and 1 percent for the average income. Interestingly, larger values in the years since the last retrofit, the average income, and the population all caused a reduction in the sales index. The presence of skylights led to an increase in the sales index. Of course, a statistically significant regression does not itself prove a causal link. There may be other unconsidered factors that are themselves correlated with sales index and the presence of skylights, e.g., the amount of local competition, but at least there is some evidence that the lighting conditions provided by the skylights are appreciated. Interviews with shoppers in the skylit stores revealed an almost total lack of awareness of the skylights but a clear perception that the store was cleaner and more spacious than other similar stores. This suggests that it was the contribution of the skylight to the visual environment in the store that was responsible for the impact on the sales index. If this is so, then there are many ways to create an attractive visual environment in a store, the use of skylights being just one.

6. Some misunderstandings

Synopsis: There are a number of papers on daylighting in schools that are widely misunderstood. These papers suffer from problems in experimental control and/or in interpretation. Further study is necessary before clear conclusions about the value of daylighting in schools can be drawn.

There are a number of publications relevant to the benefits of having daylight in schools that have been widely reported and used by enthusiastic advocates as proof of the benefits of daylighting in general. This section attempts to re-establish a balance by reviewing each publication and pointing out its merits and limitations.

The first of these is a report by the Heschong-Mahone Group (Heschong-Mahone 1999b, summarized in Heschong et al., 2002b). In this paper, an extensive epidemiological study of the effect of daylight in school classrooms on the standardized test scores for reading and mathematics is reported. The test scores of elementary school children in grades 2 to 5 were examined in three different school districts. Such children are typically assigned to a single teacher in a single classroom for the school year. The quantity and quality of daylight in the classrooms were rated, based on expert opinion, on a six-point scale from 0 = no daylight to 5 = sufficient and uniform daylighting most of the year. For one school district (Capistrano, CA), multiple linear regression equations were used to examine the effect of fifty different factors on the change in test scores from fall to the following spring. The regression equations, which in total explain about 25 percent of the variance in the data, show that children in the classrooms with the best daylighting achieved a 20 to 26 percent greater improvement over the year than average. The results in the other two districts (Seattle, WA and Fort Collins, CO) used only the test scores taken at the end of the school year. Nonetheless, children in classrooms with the best daylighting again showed higher end-of-year test scores than children in classrooms with no daylighting.

Clearly, this is a gallant attempt to quantify the effects of providing daylighting in an important area of application, using an extensive database, and a thoughtful analysis. As such it is to be applauded, but it does have some limitations. These limitations fall under the headings of effect size, causation, and implications.

The actual size of the effects associated with the level of daylight has been a source of confusion for several readers (see discussion of Heschong et al., 2002b). The quantity most commonly used to describe the effect size of a variable in multiple regression is the increase in variance explained when the variable is added to the regression equation, although what that is depends not only on the effect of the variable but what other variables have already been considered. For daylight, the additional variance explained was only 0.3%, which indicates that daylight has only a small effect. For comparison, Gifford et al. (1997) showed that the effect size of increasing illuminance on office work over a range of 70 lx to 1962 lx was 3.2 percent. However, Heschong et al. do point out that, for their data, an effect size for daylight of 0.3 percent puts it amongst other factors that are believed to be educationally important such as participation in a gifted and talented program (0.3%), the number of absences (0.1%), and the size of the school (0.1%). The factor that explains most variance is the grade of children tested (Grade 2 = 18.4%; Grade 3 = 2.6% and Grade 4 = 0.1% for reading, and Grade 2 = 14.9%; Grade 3 = 6.4% and Grade 4 = 0.6% for math).

As for causation, it is important to appreciate that the relationship between the provision of daylight and children's test scores shown demonstrates a correlation and not a causation. Heschong et al. recognize this limitation and offer some possible casual factors that might lead to a correlation between daylight availability and test scores, namely increased visibility, enhanced pupil and teacher mood, and improved pupil health. Further, in a re-analysis report they examined a possible source of bias; i.e., allocating better teachers to classrooms with better daylighting. No such bias was found in the dataset. Despite this elimination of one possible sources of bias, it is worth noting that the principle behind epidemiology is that by taking a large enough sample, differences other than the variable of interest will be averaged out. For this reason, epidemiologists tend to only accept conclusions where the effect is large (Taubes, 1995), certainly much larger than that shown in this paper.

As for the implications, it is sometimes asserted, although not by the authors, that this study has shown that daylight, *per se*, is a powerful influence for the good in education. Even if the results of Heschong et al. (2002b) are taken at face value, they demonstrate the error of this view. Although most of their analyses show an improvement in test scores with more daylight, there is one analysis for skylights that shows a reduced improvement in test scores with greater daylight. This deterioration is explained by saying that the skylight design allowed patches of sunlight to strike the walls and students desks, with consequent potential for visual and thermal discomfort. This emphasizes that it is not daylight *per se* that enhances education, but the way that it is delivered.

Two other papers that have been widely used to demonstrate the value of daylight are Hathaway et al. (1992) and Hathaway (1994). In this study, changes in the scholastic performance, absenteeism, physical development, and dental health of children were examined in five Canadian schools over two years. The schools were lit with electric light of different spectra. The papers conclude that marked improvements in academic performance, physical growth, and dental health can be achieved by using full-spectrum fluorescent lighting with an ultra-violet component rather than conventional fluorescent lighting. Given that daylight is a ideal source for delivering full-spectrum lighting with an ultra-violet component, it has been argued that these benefits can also be gained by the provision of daylight. Indeed, the title of Hathaway (1994) is "A study into the effects of light on children: A case of daylight robbery." Unfortunately, this study has been severely criticized for numerous methodological faults and analytical flaws and cannot be regarded as proving anything (Veitch and McColl, 1994; Rusak et al., 1996). Further, another study of the effects of fluorescent lamps of different spectra, including both conventional spectra and one simulating daylight, failed to show any effects of the different spectra on measures of learning or health of schoolchildren (Landrus and Larkin, 1990)

The final paper is that of Kuller and Lindsten (1992). This work examined the effect of light on the production of the stress hormone cortisol, the behavior, the body growth, and the absence of children from school, over a school year. The children occupied four different classrooms, all situated in Malmo in southern Sweden, where daylight availability is limited in winter. The lighting of the classrooms differed in the forms of lighting: one had north-facing windows and conventional 3,000K fluorescent lighting; another had a large skylight and full-spectrum fluorescent lighting; the two others had no form of daylighting but different forms of fluorescent lighting, one with 3,000K lamps and the other with full-spectrum fluorescent lighting. As a result of these differences, the amount of light and the spectrum of light in the four classrooms varied dramatically over the year. The two classrooms without any form of daylighting had illuminances in the range 200 to 400 lx throughout the year, while the classroom with windows showed a range of illuminances from 450 to 1300 lx, and the classroom with a skylight showed a range of illuminances from 300 to 6,950 lx at noon over the year. No statistically significant differences between classrooms were found in body growth or absences. What was found was a statistically significant interaction between the concentration of cortisol and classrooms. Children in all four classrooms showed a variation in cortisol concentration over the year (Figure 10), but the children in the classroom without daylight and with the 3,000 K fluorescent lamps reached a minimum at a different time of the year to the children in the other classrooms. Further, the cortisol concentration was related to observations of the children's ability to concentrate and sociability, ability to concentrate being greater at low cortisol concentrations and sociability being greater under higher cortisol concentrations.

Based on such results, the paper concludes that windowless classrooms should be avoided for permanent use. This conclusion may be wise advice, but it does not follow from the data. Only one of the windowless classrooms shows a difference in the timing of the minimum cortisol concentration, the other showing the same pattern over time as the two classrooms with daylight. A more accurate conclusion might be that work in environments where stimulation of the circadian system is limited may cause disturbances in the production and timing of hormones. It may well be that daylight provided through windows or a skylight is a practical solution to this problem, but a higher illuminance and a light spectrum matched to the circadian system would be another.

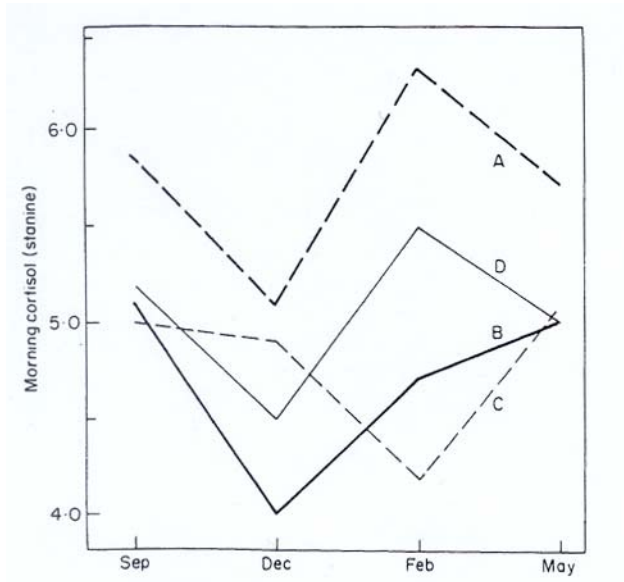

Figure 10: Morning (7 a.m.) cortisol at four different times of the year in four classrooms: a) windows and warm white fluorescent tubes; b) skylight and daylight fluorescent tubes; c) windowless and warm white fluorescent tubes; d) windowless and daylight fluorescent tubes (Kuller and Lindsten, 1992).

This examination of some of the papers relating to the benefits of daylight in schools should not be taken to mean that the presence of daylight in the classroom has no positive effects. Rather, it should be taken to mean that this important topic deserves more study. Certainly, an attempt to replicate Heschong et al (2002b) findings would be of value. Education matters to a lot of people, so even small effects are of value.

7. Conclusions

From the literature reviewed it is possible to draw the following conclusions

1. Physically, daylight is just another source of electromagnetic radiation in the visible range. Electric light sources can be constructed to closely match a spectrum of daylight, but none have been made that mimic the variation in light spectrum that occurs with daylight at different times, in different seasons, and under different weather conditions.

2. Physiologically, daylight is an effective stimulant to the human visual system and the human circadian system.

3. Psychologically, daylight and a view are much desired.

4. The performance of tasks limited by visibility is determined by the stimuli the task presents to the visual system and the operating state of that system. Daylight is not inherently better than electric light in determining either of these factors. However, daylight does have a greater probability of maximizing visual performance than most forms of electric lighting because it tends to be delivered in large amounts with a spectrum that ensures excellent color rendering.

5. There can be no guarantee that daylight will always be successful in maximizing visual performance. Daylight can cause visual discomfort through glare and distraction, and it can diminish the stimuli the task presents to the visual system by producing veiling reflections or by shadows. The effectiveness of daylight for visual performance will depend on how it is delivered. The same conclusion applies to electric lighting

6. People will take action to reduce or eliminate daylight if it causes discomfort or increases task difficulty.

7. The performance of both visual and non-visual tasks will be affected by disruption of the human circadian system. A disrupted circadian system will also create long-term health problems. Exposure to bright light during the day and little or no light at night will accurately entrain the circadian system. Daylighting is an attractive way to deliver bright light during the day.

8. Different lighting conditions can change the mood of occupants of a building. However, there is no simple recipe for what lighting conditions produce the most positive mood. Windows are strongly favored in work places for the daylight they deliver and the view out they provide, as long as they do not cause visual or thermal discomfort or a loss of privacy. Whether windows will produce an improvement in mood seems to depend on what the individual's preferences and expectations are. For people who prefer daylight but who have become

accustomed to little daylight , moving into a well daylighted space can be expected to lead to an improvement in mood that will diminish over time as new expectations are established. For people who prefer daylight and who are accustomed to a lot of daylight, moving into a space with little daylight is likely to lead to a deterioration in mood that will recover over time.

9. The understanding of how mood influences productivity is weak. Different studies have emphasized worker happiness, well-being, and job satisfaction as predictors of productivity while others have suggested that productivity is itself a generator of feelings of happiness, well-being, and job satisfaction. The basic problem for daylighting is that mood is subject to so many influences that unless the lighting is really uncomfortable, its influence is likely to be overshadowed by many other factors.

10. Exposure to daylight can have both positive and negative effects on health. The strongest effects occur outdoors. Exposure to daylight outdoors can cause tissue damage, which is bad, and generate vitamin D, which is good. Daylight and sunlight delivered through glass will have much less short wavelength ultra-violet (UV-B) radiation than the same radiation outdoors, but can still have adverse effects on people who are sensitive to ultra-violet radiation. Daylighting that makes what needs to be seen difficult to see can cause eyestrain. Conversely, daylighting that makes what needs to be seen easy to see can reduce eyestrain. Windows that provide a view out as well as daylight, can reduce stress and hence reduce the demand for health services. Daylight reduces the incidence of health problems caused by the rapid fluctuations in light output typical of electric lighting.

11. A wall containing windows costs more to construct and maintain than one without. These costs may be offset by reductions in building operating costs. However, the presence of windows is believed to have a positive effect on the rental value of a space.

12. Daylighting of a conventionally windowless retail space can have a positive effect on sales.

8. Recommendations for research

From the above conclusions, four topics that deserve research stand out. They are:

- Reducing discomfort caused by windows
- Quantifying the financial return on windows
- Exploring the impacts of daylight operating through the circadian system
- Testing the biophilia hypothesis

There are many other topics that could be examined, but some, such as examining the effect of daylight on visual performance, seem unnecessary as knowledge in that area is already sufficient to predict the results. Others, such as examining the effect of daylighting on mood and hence productivity, could be undertaken but given the amount of work that has already been done in this area and the confusing pattern of results obtained, the probability of success is low unless more sophisticated concepts and measurement methods are adopted.

8.1 Reducing the discomfort caused by windows

This is a technological project. The rationale for this project is that, while people claim to desire daylighting, they will act to eliminate or reduce it whenever it causes any discomfort or task difficulty. Further, human inertia usually ensures that once such action is taken, it may not be reversed for a long time. If the ultimate aim is to increase the use of daylight in buildings and thereby reduce the use of electric lighting, then it would seem sensible to try to do two things: first, to minimize the prevalence of conditions under which actions aimed at reducing or eliminating daylight occur, and second, to develop methods whereby the actions taken to reduce or eliminate daylight are reversed at the end of each day.

Possibilities for minimizing the conditions under which actions aimed at reducing or eliminating daylight occur involve matching the luminance of the interior of the window wall to the view through the window, manipulating the shape of the reveal around the window to provide a luminance buffer, and developing blinds or screens that would reduce sky luminance without eliminating daylight or a view out.

Possibilities for reversing actions taken to reduce or eliminate daylight would require the development of systems for automatically opening and/or withdrawing blinds at the end of the day. This approach is analogous to that used in occupancy sensors where the switch-off is automatic and the switch-on is manual. The concept is to use human inertia in the interests of saving energy.

8.2 Quantifying the financial return on windows

This is an epidemiological project. The problem faced by anyone trying to quantify the cost / benefit ratio for daylighting is that, while the costs can be easily estimated, the financial benefits cannot. The idea behind this project is to measure what people are prepared to pay for daylighting in different forms, ignoring the reasons why. The value of daylighting can be quantified by the rental value of the property. At the moment, the only information available on this topic considers the extremes of the range of possible conditions, from a windowless building to a windowed building. What is necessary is to fill in this range so that the value of different sizes, numbers, and types of windows can be quantified. One approach to doing this would consist of a large-scale survey of rental values achieved for buildings of the same function, e.g., offices, but with different levels of daylighting.

8.3 Exploring the impact of daylight operating through the circadian system

This is the only area of research suggested that directly addresses the question of daylighting and productivity. The reason for this is that the circadian system provides a plausible mechanism whereby daylight might have a marked effect on the performance of many tasks, not just visual tasks. This is particularly so in high northern or southern latitudes, where exposure to daylight during the journey to work is limited for several months of the year. This could be done as a laboratory experiment or a field experiment, provided a well-established protocol for measuring productivity were in place. If it could be shown that exposure to daylight increased productivity during the day in winter months but not in the summer months, then a case for greater use of daylight could be made.

8.4 Testing the biophilia hypothesis

This is a fundamental topic but one which has important implications for the value of windows, for two reasons. The first is that the biophilia hypothesis is the main reason found in this review why windows are inherently better for people than electric lighting. All the other physiological effects of windows can, in principle, be fulfilled by electric lighting, given enough care and expenditure. But if contact with nature is really an essential part of life for people, then windows should be a legally required component of many buildings, as they are in some European countries. The second is that if the biophilia hypothesis is correct, then a view out should be much more important than letting daylight in. It is important to distinguish between these two attributes because some forms of daylighting provide both (windows), while others emphasize one at the expense of the other (e.g., a clerestory window emphasizes the provision of daylight relative to the view out). To test the biophilia hypothesis requires an experiment in which the magnitude and natural content of the view out would be manipulated and the response in terms of mood, behavior, and performance is measured over a sustained period.

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